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FACTORS AFFECTING THICKENING IN LIQUID SOLIDS SEPARATION

George J. Schroepfer, et al

Minnesota University
Minneapolis, Minnesota

31 March 1964

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Factors Affecting Thickening in Liquid Solids Separation

Final Report

of

Investigation Sponsored by Research Grants
No. WP205
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by
George J. Schroepfer
N. R. Ziemke

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SPONSORSHIP AND STAFF

This research project titled "Thickening in Liquid Solids Separation" was sponsored by the National Institutes of Health under Research Grant No. 205 and operated under the University of Minnesota budget number 0632-5200. This is the final report on this project and covers the period from October 1, 1960 to March 31, 1964.

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A. INTRODUCTION

This is the final report of a research program titled "Thickening in Liquid Solids Separation" conducted by the Sanitary Engineering Division of the University of Minnesota. This report covers the period from October 1, 1960 to March 31, 1964.

1. Research Aims and Objectives

The general objective of the research program was to investigate the factors affecting the thickening of various types of liquid-solids suspensions by gravity sedimentation. The more specific aims of the program were as follows:

1. To study the fundamental concepts and mechanisms involved in the gravity thickening process on both a batch and continuous flow basis,
2. To determine the significant loading parameters which affect the performance of the continuous flow thickening process and attempt to numerically evaluate the relationship between loading and performance of the process as applied to various solids suspensions and sludges,
3. To determine if the results of batch thickening tests on a particular solids suspension can be used to predict the limiting load and design capacity of a plant scale continuous flow thickener,
4. To develop a rational method for the design and operation of full scale thickeners.

In addition, ancillary studies were aimed at developing an instrument which could be used to quickly estimate the solids concentration and sludge density at various points in a continuous flow thickener.

2. Research Plan

The research plan which was used to accomplish these aims involved the application of the gravity thickening process to various solids mixtures including synthetic suspensions and actual waste sludges from various water and waste water treatment processes. A separate series of tests was conducted for each different liquid solids mixture and included concurrent batch tests and steady state continuous flow studies. The continuous flow studies were carried out in a laboratory scale pilot plant designed so that the operating and loading conditions could be controlled in accordance with the test plan. The results of the batch tests and pilot plant tests in each series were analyzed to study the mechanisms of thickening to evaluate the factors which affect the performance of the thickening process and compare the results of batch and continuous flow thickening. During the program of pilot plant tests, several instruments for determining solids gradients in the sludge blanket of a continuous flow thickener were designed and tested in the pilot plant.

B. THEORY AND MECHANISMS OF THICKENING

1. Review of Previous Work

There are a number of reports available which have attempted to analyze the theory and mechanisms of the batch and continuous flow thickening process. Notable among these are the early reports by Coe and Clevenger (1) and Kynch (4) and more recent reports including work by Comings et al (3), Talmadge and Fitch (5) and Hassett (7) (8) and (9). In general, most of these reports have attempted to develop the basic theory of the batch thickening process and some have attempted to use batch tests as a method of predicting the limiting capacity of continuous flow thickeners. This report will briefly review this early work and discuss the fundamental concepts involved in batch and continuous flow thickening in the light of the results of these investigations.

Any discussion on the theory of the gravity thickening process would undoubtedly start with the classical work of Coe and Clevenger who have been credited with making the first quantitative description of the process. Their investigations were specifically applied to slime thickening tanks used in the mining industry for which they developed a method of analyzing the results of batch settling tests to predict the capacity of continuous flow thickeners. These writers were the first to suggest that the velocity of fall of a liquid solids interface in a batch settling test was primarily related to the local concentration of particles at the interface. They also observed and described separate zones of solids concentration that occur in the sludge blanket of continuous flow thickeners. From the results of their work they defined these zones as (a) a top zone of relatively clear liquid, (b) an intermediate zone of almost constant solids concentration and (c) a bottom zone in which the solids concentration increases to the bottom discharge concentration. In addition to these zones they observed a narrow zone at the bottom of the thickener in which the solids concentration increased quite rapidly.

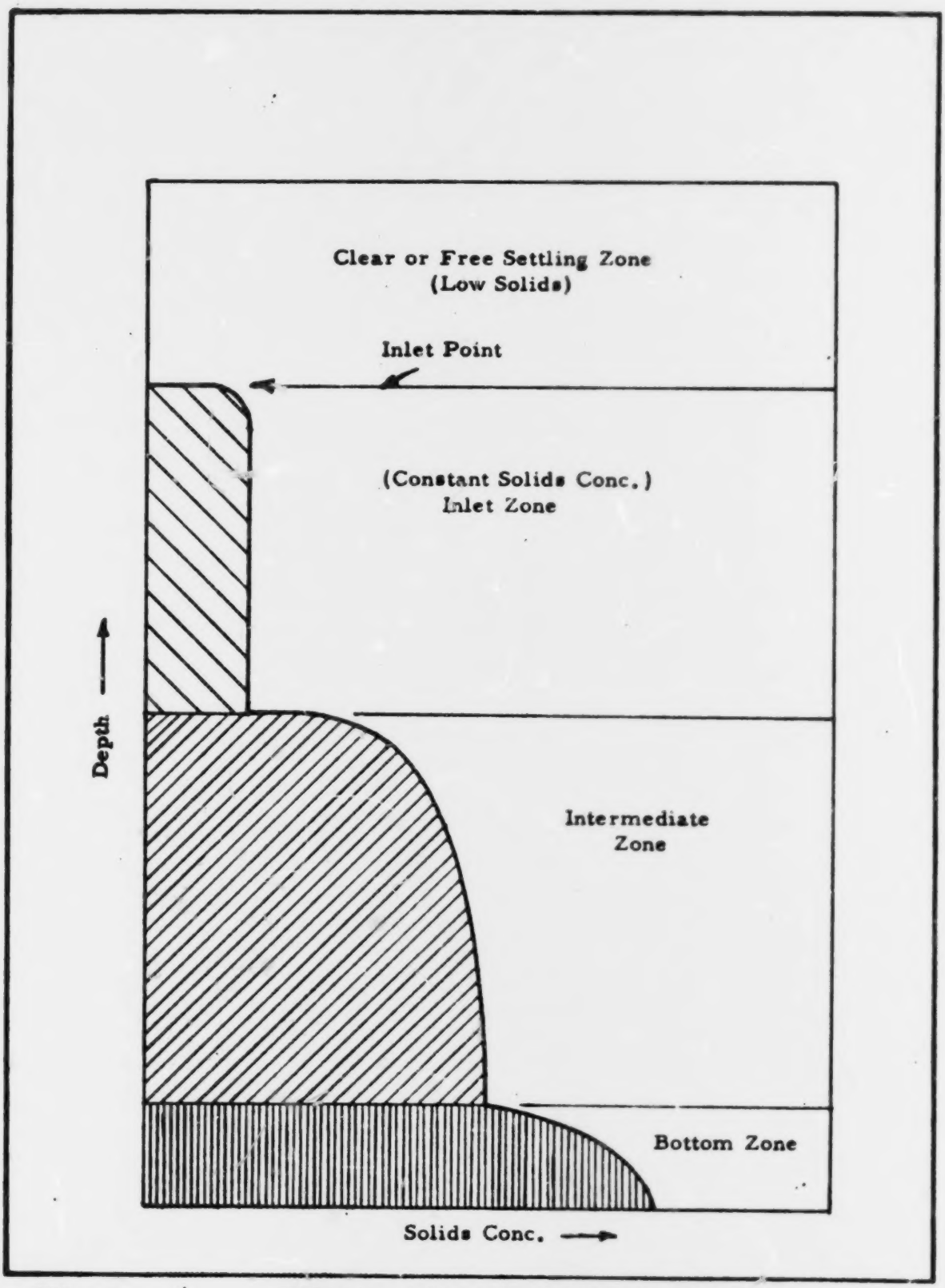


FIG. 1 **TYPICAL CONCENTRATION GRADIENT DIAGRAM**

This bottom zone was also observed by Darby (2) and Comings (3) and has been referred to as the "rake action"zone. Based on observations made during the present study and the work of Hassett, this narrow bottom zone has been found to occur even without the presence of rake action or flight scrappers. A typical solids concentration gradient diagram showing the zones of concentration occurring in a continuous flow thickener is presented in Figure 1. A more detailed discussion of these zones will be given later.

The method proposed by Coe and Clevenger for predicting thickener capacity was based on the analysis of batch test results to evaluate the velocity of fall of the solids interface as a function of the solids concentration at the interface. This relationship was evaluated by observing the initial rate of interface lowering in batch tests conducted at various initial solids concentrations.

In 1952, C. J. Knych presented a paper on a theory of batch sedimentation. He developed a mathematical model of the process which occurs in the quiescent settling of liquid solids suspensions. His hypothesis was also based on the postulate that the settling velocity of a particle in an interface is a function of only the local solids concentration around the particle and was developed to mathematically show the existence of concentration waves propogated upward from the bottom of the settling container. The following brief review of the Kynch theory is based on the work of Talmadge and Fitch. Starting with the Kynch postulate it follows that:

$$V = f(C)$$

where V = velocity of fall of the interface

C = solids concentration

In a batch test starting at uniform solids concentration all of the particles begin settling at the same velocity. As the particles begin to build up on the bottom they must pass through all concentrations between the starting concentration and that of the deposited solids. If at any layer

of intermediate concentration between these two concentrations the solids passing into the top of the layer are more than that passing out the bottom, a zone of this intermediate concentration must start building up or rising to the surface. These waves of concentration are propogated upward. The development by Kynch indicates that the upward movement or velocity of these concentration waves is constant. This he mathematically explained in the following manner.

Visualize an infinitely thin layer as the upper boundary of a zone having a concentration of C, originating at the bottom at time zero and moving upward with a velocity of U. The solids passing into this layer from above are at a concentration (C - dC) and are settling at a velocity of (V + dV) with respect to the tube and a velocity of (V + dV + U) with respect to the layer. The concentration of solids settling out of this layer will be C with a velocity of V with respect to the vessel and (V + U) with respect to the layer. Since the concentration of the layer is constant, the quantity of solids settling into the layer must equal the quantity settling out and a balance can be made as follows:

$$(C - dC)\, At\, (V + dV + U) = CAt\, (V + U)$$

where A is the area and t is the time.

Solving for U and neglecting infinitesimals of the second order we get

$$U = C \frac{dV}{dC} - V$$

and since $V = f(C)$ and $\frac{dV}{dC} = f'(C)$ then

$$U = Cf'(C) - f(C)$$

Since C is a constant for the layer, $f'(C)$ and $f(C)$ must have fixed values and therefore U must also be constant.

The fact that U is constant can be used to determine the solids concentration at the interface. If C_o and H_o are the initial solids concentration and height respectively, then the total weight of solids in the column is $C_o H_o A$. Since a concentration layer, $C > C_o$, is propagated

from the bottom at a velocity U, when this layer reaches the liquid solids interface all of the solids must have passed through it. If this layer reaches the interface in time t then the solids having passed through the layer is given by CAt(V + U) and this must be equal to the total weight of solids in the column or

$$C_o H_o A_o = CAt(V + U)$$

Since U is constant and H is the height of the interface at time t it follows that

$$U = \frac{H}{t}$$

substituting this and simplifying

$$C = \frac{C_o H_o}{H + Vt}$$

V is equal to dH/dt at the point on a plot of H versus t (settling curve) at which the layer having a concentration C reaches the interface as shown in Figure 2. V is then the slope of the tangent to the curve at (H, t). The intercept of this tangent on the H axis is H + Vt and is shown as H'. By substituting H' for H + Vt in the above equation it is shown that $CH' = C_o H_o$ and it follows that H' is the height the solids would occupy if all of the solids present were at the same concentration C as at the interface. Thus for any arbitrarily selected value of H' the corresponding value of C can be calculated. The velocity of fall V can then be determined as the slope of the line from H' tangent to the settling curve and V as a function of C can be completely developed from one settling test.

Hassett (7, 8, 9) Talmadge and Fitch (5) and Coe and Clevenger (1) have attempted to apply the relationship between V and C to develop a method to predict the minimum area requirement for a continuous flow thickener in order to discharge a specified bottom or underflow concentration. These reports were discussed in Progress Report No. 145 S and will not be presented here.

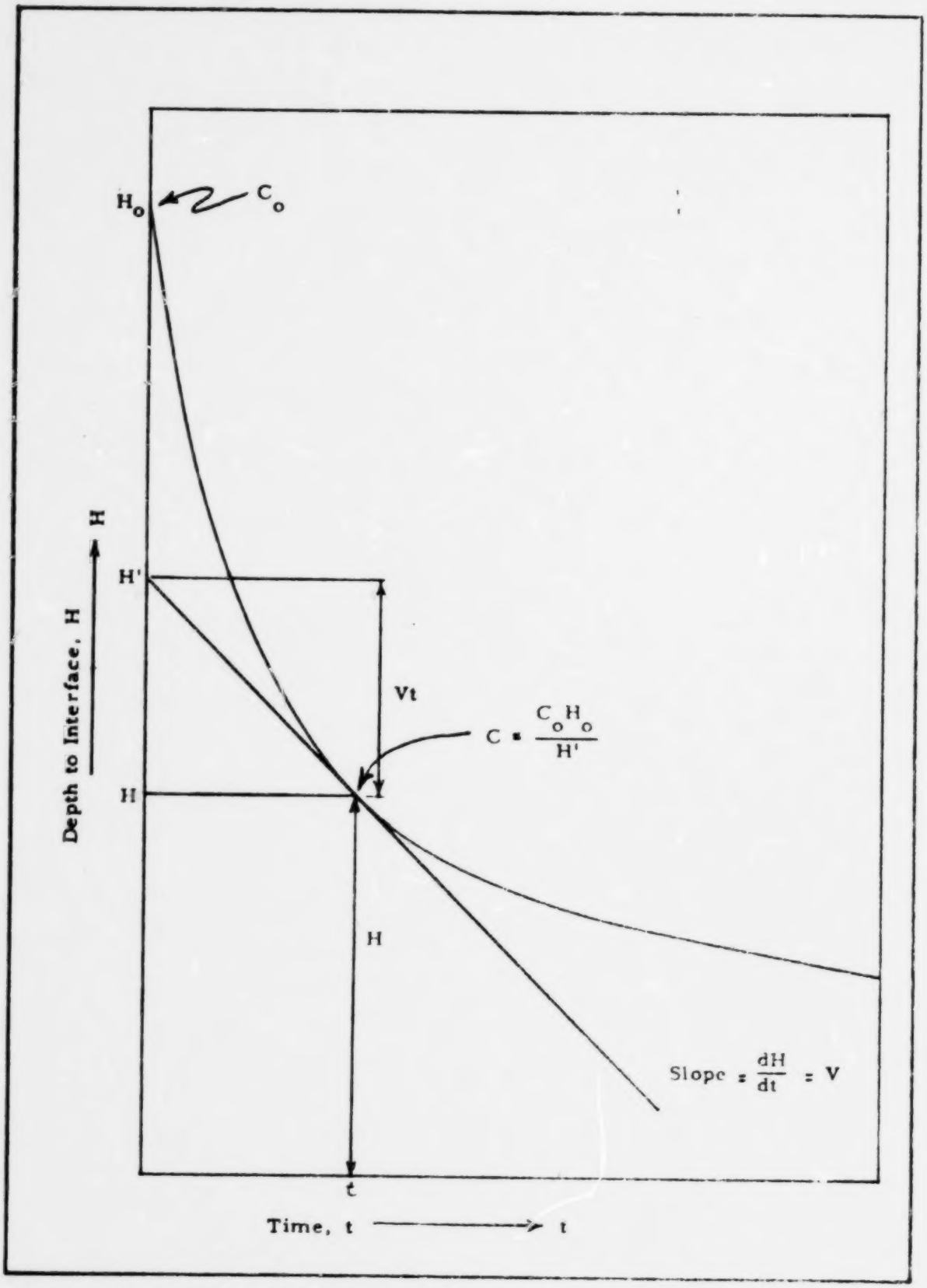


Fig. 2 APPLICATION OF KYNCH ANALYSIS TO A TYPICAL BATCH SETTLING CURVE

2. Application of Batch Tests to Continuous Flow Tests in Present Studies

A large number of batch tests were conducted along with the continuous flow pilot plant tests on a variety of synthetic mixtures and actual waste sludges during these investigations. On a practical basis one of the major objectives of this research was to develop a method of analyzing batch test results to predict the performance and limiting capacity of continuous flow thickeners. The method that was developed can be best illustrated by analyzing an example of a hypothetical test suspension.

a. Analysis of a Hypothetical Batch Settling Test

To begin with it should be pointed out that some of the ideas presented here are not original. Also it should be emphasized that the analysis is based on liquid-solids mixtures which are in a concentration range in which a somewhat definite liquid solids interface is formed and the particles settle "enblock" rather than at various rates as might be true at lower solids concentrations.

Although it is difficult to define a typical batch settling test since each different suspension appears to exhibit its own individual characteristics, the settling curve shown in Figure 3 can be used as a hypothetical case to describe the type of analysis that was used in these investigations. The method proposed by Coe and Clevenger (1) and that proposed by Kynch (4) for determining the relationship between the interface velocity (V) and the solids concentration (C) have been briefly described earlier. It was found in this investigation that the method proposed by Kynch gave more consistent results and was used exclusively in all of the tests reported herein. This does not presume that the authors believe that the Kynch theory is entirely correct in all ranges of concentration because there is some evidence which does not entirely substantiate his theory. However,

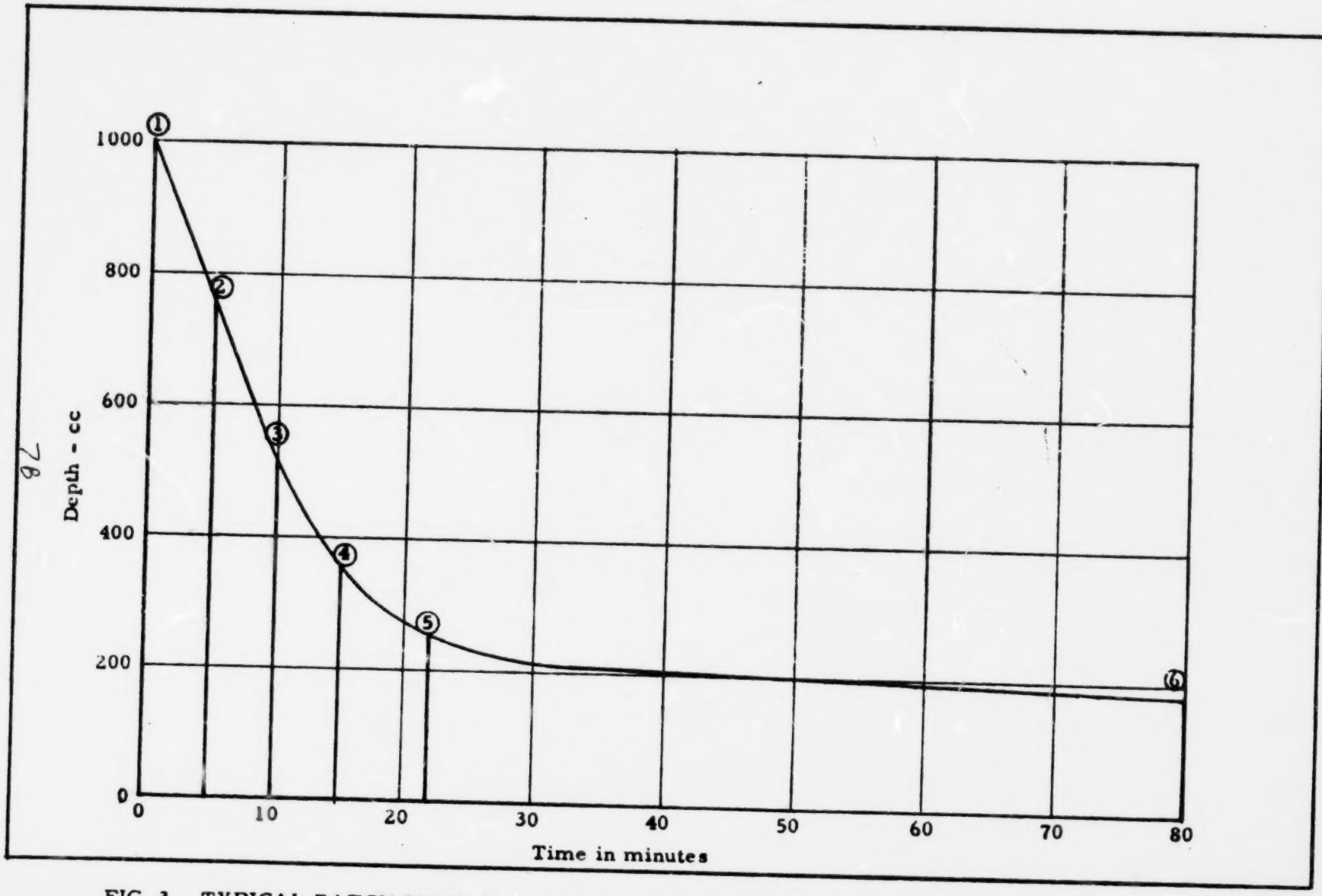


FIG. 3 TYPICAL BATCH SETTLING CURVE - DEPTH TO SOLIDS INTERFACE VS. TIME

this investigation has shown that if the batch settling test is conducted at or near the raw feed solids concentration that was to be used in the continuous thickener, the Kynch analysis provided the most consistent relationship between V and C.

Most of the batch tests were conducted in one liter cylinders and the depth recorded in cubic centimeters vs time as shown in Figure 3. If in this example the initial solids concentration (C_o) and the initial depth (H_o) are known, a visual picture of the process that occurs according to the Kynch theory is shown in Figure 4 for the six points selected on the settling curve. Referring to Figures 3 and 4 at time zero (point 1) the solids concentration in the cylinder and at the interface is C_o and the depth is H_o. At point 2 there is a secondary interface being propagated up from the bottom (usually not visually evident) which has not as yet reached the upper interface which is still at concentration C_o. At point 3 the interface being propagated upward from the bottom has just reached the top interface and there is a transition in the settling curve to a slower settling rate. At points 4, 5 and 6 the interface solids concentration begins to increase and the rate of settling decreases. If the solids in the suspension were stable, and allowed to settle long enough the interface would cease to settle and become stable. The interface solids concentration at any of these points can be computed by the Kynch analysis as described earlier.

If in this typical example we assume an initial solids concentration of 1.0% and that the concentration waves propagated from the bottom increase in a linear fashion as in the Kynch analysis, Figure 5 shows the batch solids concentration gradients for the six points indicated on the settling curve. These were computed from the ideal case in which it was assumed that there were zero solids above the interface and that all of the original solids must be accounted for in the solids gradient. If this picture were carried beyond point 6 where settling virtually stopped, the bottom and the interface solid concentration would be nearly the same and the bottom concentration would reach what will be referred to in later work as the ultimate concentration

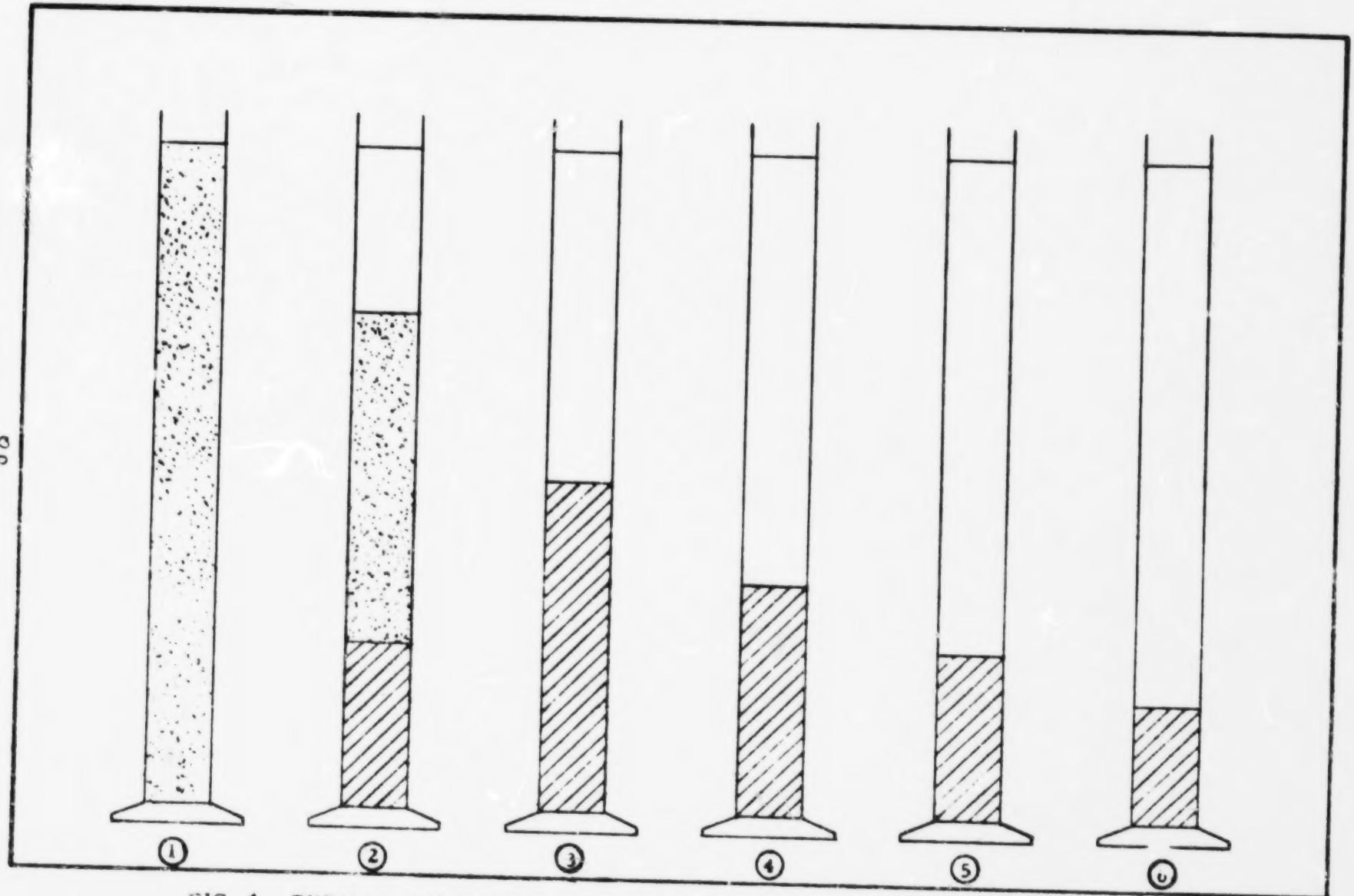


FIG. 4 TYPICAL BATCH SETTLING TEST SHOWING INTERFACE LEVEL AT VARIOUS TIME INTERVALS FROM START OF TEST

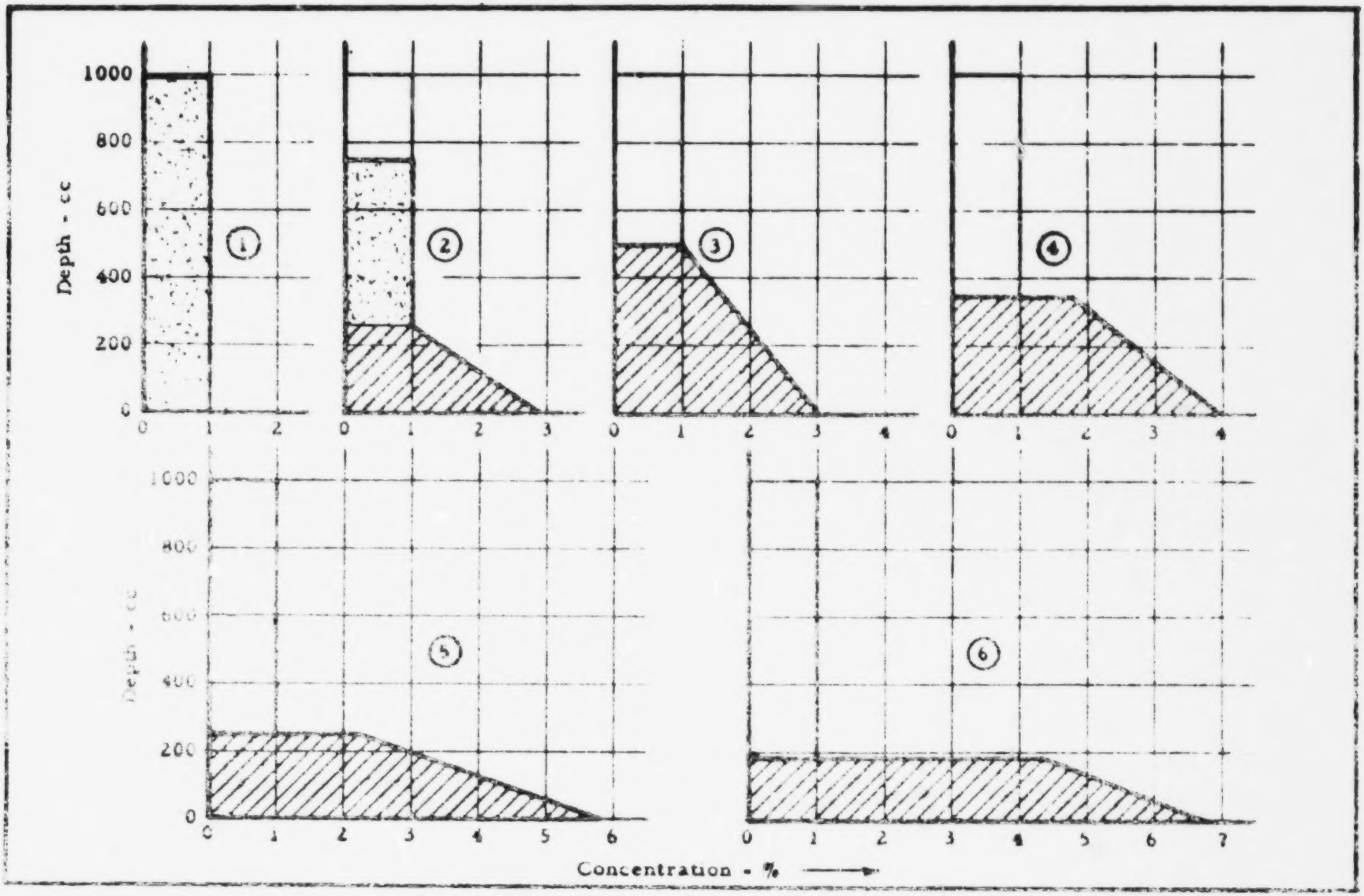


FIG. 5 TYPICAL CONCENTRATION GRADIENT DIAGRAMS FOR BATCH SETTLING TEST

(C_u). Using this same approach, the variation in the bottom and interface solids concentrations with time for this typical example are shown in Figure 6. This would indicate that in this idealized example that a bottom concentration approaching the ultimate concentration is reached in a fairly short time beyond which there is a very slow increase to the ultimate concentration. This brings up some very important questions that will be discussed later in this report. First, does each different suspension have a characteristic ultimate concentration and second, does the depth of the sludge blanket which is directly affected by the restriction of the bottom have an appreciable affect on the ultimate concentration?

Continuing with the typical example of the batch settling test, the Kynch method can be used to compute the interface solids concentration at any point on the curve and the velocity determined by the slope of the tangent to the point. This relationship is shown in Figure 7. It should be recognized, however, in applying this theory to subsequent data that at low solids concentrations the solids liquid interface is not defined or clear cut (solids do not settle "enblock") and it is questionable whether the Kynch analysis is valid below this limiting concentration. If however the relationship between V and C can be established, it can easily be used to compute a batch loading or flux (lbs solids passing one sq ft per day) curve in terms of solids concentration as is shown in Figure 8 for the typical example. In this case it is noted that the maximum batch flux (or loading) is fairly well defined (which is seldom the case using actual waste sludges which tend to flocculate). Below this maximum batch loading concentration the quantity of solids that can settle past a unit area per unit of time decrease sharplyto anobvious zero at zero solids concentration. Above this point the flux or loading decrease more slowly to zero at a solids concentration which might be compared to the ultimate concentration C_u.

b. Application of Batch Test Results to Continuous Flow Thickeners.

In the past certain indices based on batch tests have been used to determine the relative thickening and settling characteristics of waste sludge and solids suspensions. Two of the more common of these are the sludge volume index and the sludge density index which have been used for the most part to determine the settling characteristics of activated sludge. As already mentioned several workers in the past have used batch settling tests in an attempt to develop design criteria and limiting loadings for continuous flow thickeners. These investigations were partly aimed at developing a rational method for using the results of batch settling tests to predict the limiting loading and design criteria of continuous flow thickeners especially as applied to waste sludges from water and waste water treatment plants.

From an ideal viewpoint the primary function of a continuous flow thickener is to concentrate solids in the underflow to the greatest extent that is economically feasible. In most instances, however, especially in waste treatment, a secondary function which is almost as important is to clarify the overflow liquid as much as possible to prevent the loss of solids. Since at equilibrium there must be a balance of the solids fed into a thickener and those being discharged in the overflow and underflow, it follows that if the two objectives listed above are to be achieved (minimal solids overflow) then $Q_R \times C_R = Q_{UF}\, C_{UF}$

where Q_R = raw flow rate
C_R = solid concentration in raw flow
Q_{UF} = underflow rate
C_{UF} = solids concentration in underflow

The continuous flow pilot plant tests conducted during these investigations have been carried out over a fairly wide range of loading conditions but in general the concentration of the underflow and the clarity of the overflow based on a solids balance have been used as performance criteria.

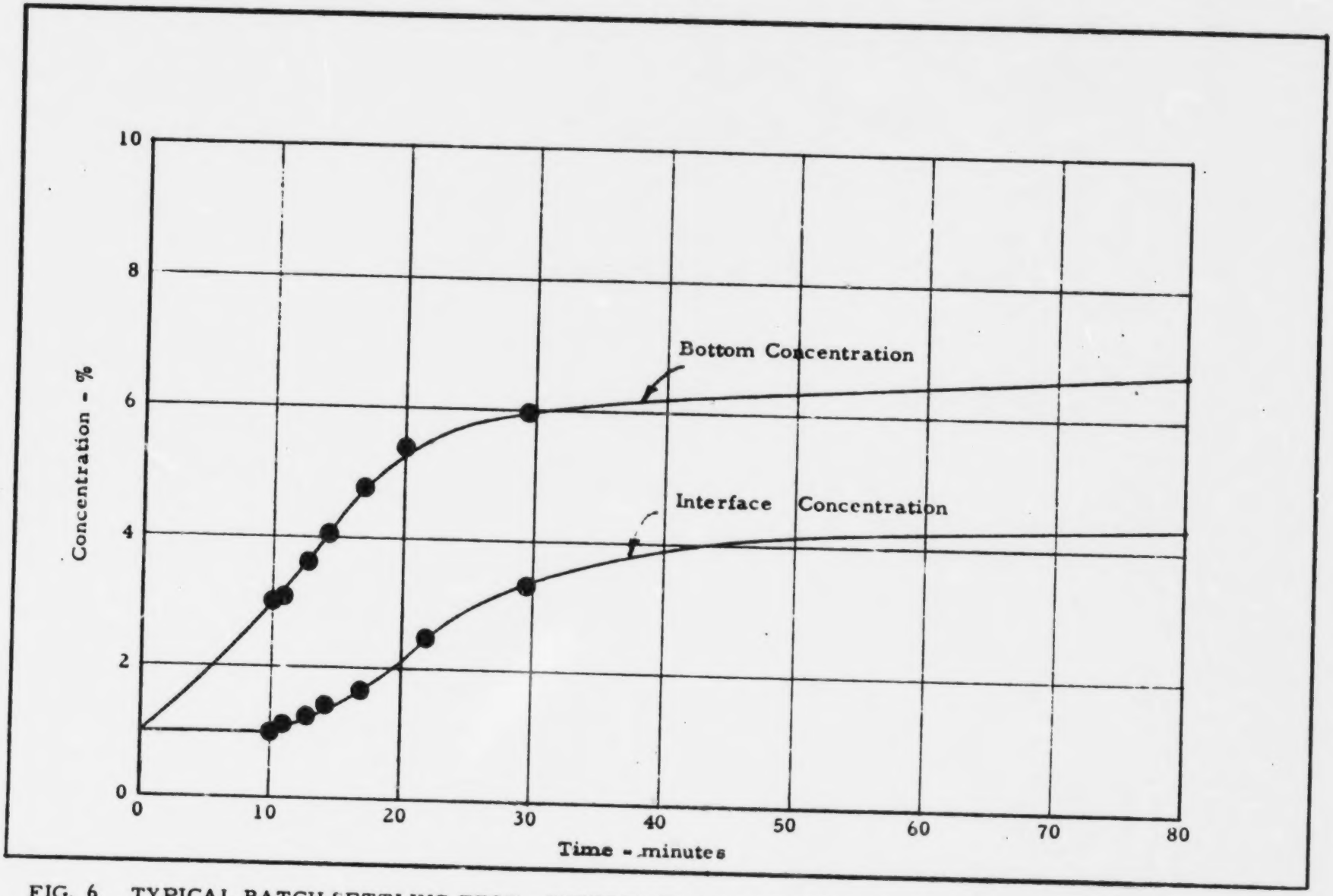


FIG. 6 TYPICAL BATCH SETTLING TEST - INTERFACE AND BOTTOM CONCENTRATIONS VS. TIME

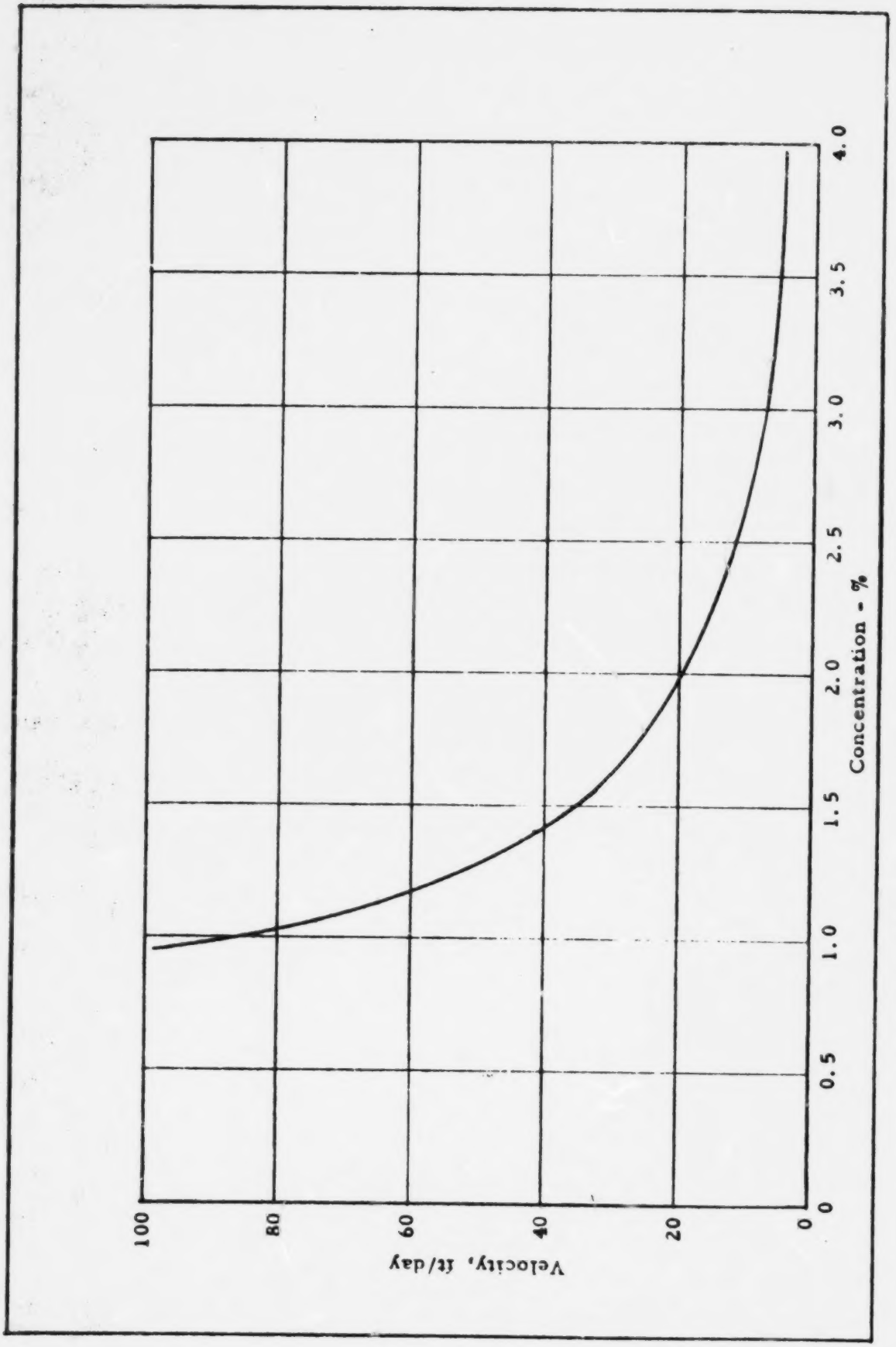


FIG. 7 TYPICAL VELOCITY CURVE

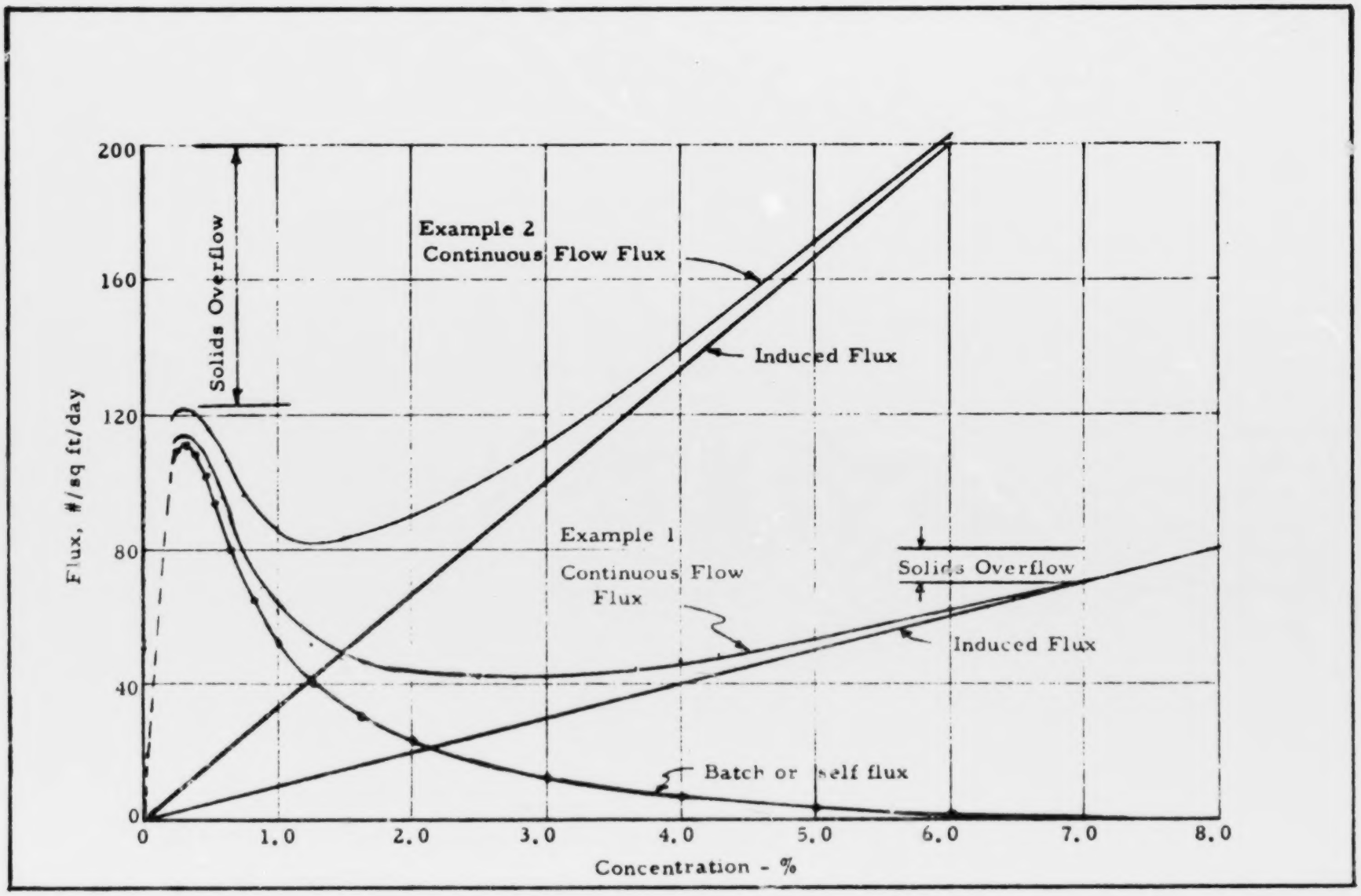


Fig. 8 TYPICAL BATCH AND CONTINUOUS FLOW FLUX CURVES

The results of the typical batch test which has been analyzed in the example above can be used to illustrate how batch test results might be applied to the design and control of continuous flow thickening units. Referring to the plot of the interface and bottom concentrations with respect to time shown in Figure 6, two important characteristics of this suspension are apparent. First, the bottom concentration increases quite rapidly during the first thirty minutes and second the limiting or ultimate concentration (C_u) would likely be near 7.0 percent even after long periods of settling. These basic characteristics determined from batch tests can be useful in designing and establishing the limiting capacity of a continuous flow thickener. Suppose for example that a continuous flow thickener was to be designed for this idealized case. The detention period should be greater than 30 or 40 min (in subsequent pilot plant tests this condition was not found to be a problem at normal tank depths). Probably more important, for a condition of minimum solids overflow and maximum solids concentration discharge in the underflow the continuous thickener should be designed so that the quantity $\frac{Q_R}{Q_{UF}} \times C_R$ is near but probably somewhat less than 7.0% (C_u). This stems from the fact that for a continuous flow thickener with no solids overflow a solids balance in the system is achieved when

$$Q_R \times C_R = Q_{UF} \times C_{UF} \quad \text{or}$$

$$\frac{Q_R}{Q_{UF}} \times C_R = C_{UF}$$

and it follows that if the value of C_{UF} required to satisfy this relationship is greater than the ultimate concentration (C_u) there must be a loss of solids in the overflow.

A method for applying batch test results to continuous flow thickening can probably be best illustrated by reviewing several examples based on the hypothetical and idealized test suspension that was analyzed above. In Figure 8, there are two examples where flux (loading) curves have been

computed from the basic batch flux curve for continuous flow situations. To begin with, it should be pointed out that the batch curve indicates what might be termed the self flux based on the velocity of fall of the particles at various concentrations when no flow is involved and the solids are allowed to pile up on the bottom of the container. If it is visualized that a solids suspension is continually introduced near the top of the container and the thickened solids and clarified liquid are taken continually from the bottom and top of the container the process is identical to continuous flow thickeners. In a continuous flow thickener there is an induced flux due to the downward velocity of the underflow which is superimposed on the self flux. This induced flux at various solids concentrations can be represented by straight lines with a slope which is a function of the raw feed flux ($Q_R \times C_R$) divided by the underflow rate (Q_{UF}). This quantity which has been referred to before has been defined and will be referred to in the remainder of this report as the concentration index.

$$\frac{Q_R}{Q_{UF}} \times C_R = \text{Concentration Index}$$

It is apparent that for a solids balance in a continuous flow thickener the flow ratio is a measure of degree that the raw solids must be increased in the underflow in order to prevent the loss of solids in the overflow.

In Figure 8 examples are shown in which the self flux and the induced flux have been combined to define the total flux curves for two different flow conditions. Before reviewing these examples however it might be well to point out two limiting conditions that are evident from an analysis of the batch test data on the hypothetical test suspension. First there is a maximum self flux at a solids concentration of about 0.3% and second, as mentioned earlier, under the conditions and assumptions made for the idealized example the maximum solids concentration characteristic for this material is about 7.0%. These two facts suggest that under continuous flow conditions the two factors which might have the most

significant effect on the performance would be the flux or solids loading (lbs solids applied per sq ft per day) and the ultimate solids concentration (C_u) characteristic of the suspension [redacted] tested. It is obvious of course that there are two extremes that are possible with respect to the limiting loading (Solids applied rate lb/sq ft/day) of a continuous thickener. First if Q_R and Q_{UF} are equal with no overflow, C_R would be equal to C_{UF} and the loading could be infinite but no effective thickening would be achieved. Second, if the concentration index were greater than C_u, even at the very lowest solids loadings some solids would be lost in the overflow. In the present investigation an attempt was made to apply batch test data to continuous flow conditions in order to predict the maximum solids loadings to give the best performance in terms of the most concentrated underflow solids and the least loss of solids in the overflow.

In example No. 1 in Figure 8 assume that the raw feed solids concentration is 1.0% and that Q_R is sufficient to produce an applied load of 80 lb/sq ft/day. Suppose also that Q_{UF} is such that the concentration index is 8.0%. The induced flux and the total continuous flow flux (self flux plus induced flux) are shown. Now if the ultimate concentration for this suspension is 7.0% then the maximum solids that can be taken out of the bottom discharge will be only 70 lb/sq ft/day and the solids in the sludge blanket will build up so that 10 lb/sq ft/day will be discharged with the overflow. Using this same example if Q_R were reduced so that the applied loading was 60 lb/sq ft/day then the concentration index would be 6.0% and there would be no solids loss in the overflow.

In example No. 2 assume again that the raw feed solids concentration is 1.0% and that Q_R is sufficient to produce an applied load of 200 lb/sq ft/day and Q_{UF} is such that the concentration index is 6.0%. The induced and total flux curves are shown. In this case it is noted that the only point where the total flux curve intersects the 200 lb/sq ft/day loading line is at a solids concentration of about 6.0%. It is difficult to theorize on what would happen under a situation such as this but subsequent pilot

plant tests have shown there is a maximum loading near or slightly above the peak batch flux (in this case at about 110 lb/sq ft/day) above which solids are carried out in the overflow. This is most likely due to the high upward overflow velocities which tend to carry solids upward and shorter overall detention times at high solids and volumetric loadings. In example 2 shown in Figure 8 it is likely that there would be solids overflow but it has been found that it is difficult to accurately predict where the equilibrium solids balance will be reached in a continuous thickener based only on batch test results.

A possible explanation of why the separation of solids in continuous flow thickeners occurs in various zones of concentration as described earlier in Figure 1 can be made from the continuous flow flux curves shown in Figure 8. In example 1 if the raw feed C_R is 1.0% at a solids loading of 40 lb/sq ft/day and the concentration index is 4.0% it is obvious that under these conditions there will not be any solids in the overflow. Under these conditions the raw solids concentration will dilute at the inlet to lowest solids concentration that will pass more than 40 lb solids per day. The zone above the inlet will be clear and the inlet zone will stay at a constant solids concentration until it reaches the influence of the bottom at which point the concentration will increase abruptly in a narrow zone to a discharge concentration of 4.0%. Now if in the same example C_R is 1.0% at a solids loading of 50 lb/sq ft/day and a concentration index of 5.0% (Q_{UF} remains the same) it is noted that part of the flux curve falls below the 50 lb/sq ft/day. This means that under these conditions, solids concentrations between about 1.5% and 4.5% cannot pass 50 lbs of solids per day and this fact causes what has been termed the intermediate zone referred to in Figure 1. In this situation there would be a clear zone above the inlet, an inlet zone at a solids concentration somewhat below the raw concentration, an intermediate zone in which the solids concentration would increase abruptly to a solids concentration of 4.5% and a narrow bottom zone in which the

solids concentration increases sharply to the discharge concentration of 5.0%. The factors which govern the depths of these various zones have not been established, however, some general observations can be made from the results of the pilot plant investigations. First if the bottom zone is present, it is usually quite narrow (one to two feet). Second, the depth of the intermediate zone appears to be related to the solids loading and concentration index. Third, if a thickener is overloaded to the point where solids are lost in the overflow the inlet zone concentration increases above that of the raw feed concentration.

3. Significant Loading and Performance Parameters for Continuous Flow Thickeners.

In current sedimentation practice where clarification is the prime concern it is common practice to design and operate the units on the basis of detention period and surface settling rate and to measure performance in terms of solids removal efficiency and clarification of the overflow liquid. In gravity thickening practice where the highest concentration of solids in the underflow is of prime importance significant loading and performance parameters are not as firmly established. It should be pointed out, however, that effective thickening should also be concerned with preventing the loss of solids in the overflow liquid. With this in mind the significant loading parameters for thickening units might include not only the detention period and surface settling rate but also the solids applied rate and some parameter which would indicate degree to which a particular solids suspension can be concentrated. The operation of a gravity thickener must satisfy a solids balance. In other words at equilibrium the weight of solids fed in must equal the weight of solids discharged in the underflow and overflow. If as suggested earlier the efficient operation of a thickener requires minimum solids overflow, the solids balance for this condition can be approximated as follows:

$$Q_R \times C_R = Q_{UF} \times C_{UF}$$

Assuming a constant area (A) and depth (D) of a thickener most of the loading parameters listed above can be expressed in terms of these four independent variables.

1. Detention period $\frac{A \times D}{Q_R}$ (usually expressed in hrs)

2. Surface Settling Rate (SSR) $\frac{Q_R}{A}$ (usually expressed in gal/sq ft/day)

3. Solids Applied Rate (SAR) $\frac{Q_R \times C_R}{A}$ (usually expressed in lb/sq ft/day)

4. Concentration Index = $\frac{Q_R \times C_R}{Q_{UF}}$ (expressed as concentration)

In all of the continuous flow pilot plant tests that were run during these investigations these loading parameters were computed and analyzed to determine their effect on the performance of the process. The performance was measured in terms of solids concentration in the underflow, the solids removal efficiency and the depth and solids concentration in the sludge blanket. It was found that the solids applied rate and the concentration index were by far the most significant parameters affecting the performance of the process.

C. EXPERIMENTAL PROCEDURES

1. Arrangement and Operation of Pilot Plant

During the first year of these investigations a continuous flow pilot plant was designed and constructed. This pilot plant was erected to remain at the laboratory and was put into operation on synthetic liquid solids mixtures that could be made up at the laboratory. In order to make pilot plant investigations on actual waste sludges that could not be transported to the University Sanitary Laboratory, a second pilot plant was constructed during the second year of study. This unit was designed almost identical to the first except that it was made in sections so that it could be dismantled and transported to various water and waste water treatment plants to make studies under actual plant conditions.

a. Description of the Pilot Plants

Since the two pilot plants were designed and constructed almost identically, only a description of the unit which was operated at the Sanitary Engineering Laboratory will be presented. A schematic flow diagram of the pilot plant arrangement is shown in Figure 9. In general the pilot plant consisted of a thickening unit and all the necessary pumps, tubing and equipment to operate the unit on a continuous flow basis. The thickening unit was made of plexiglass tube 5 inches in diameter mounted vertically on a board. The total overall depth of the unit was about 16 feet with openings for inlets or outlets spaced at one foot intervals so that the effective depth and inlet location could be varied. The unit was provided with a cone bottom to facilitate underflow removal. One half inch diameter sampling taps were spaced at 4 inch intervals along the entire length of the tube. These were provided to take samples of the sludge solids gradient in the tube and were also used as pressure taps for the measuring the pressure gradient in the tube. (This method of determining the solids gradient will be discussed later in this report.)

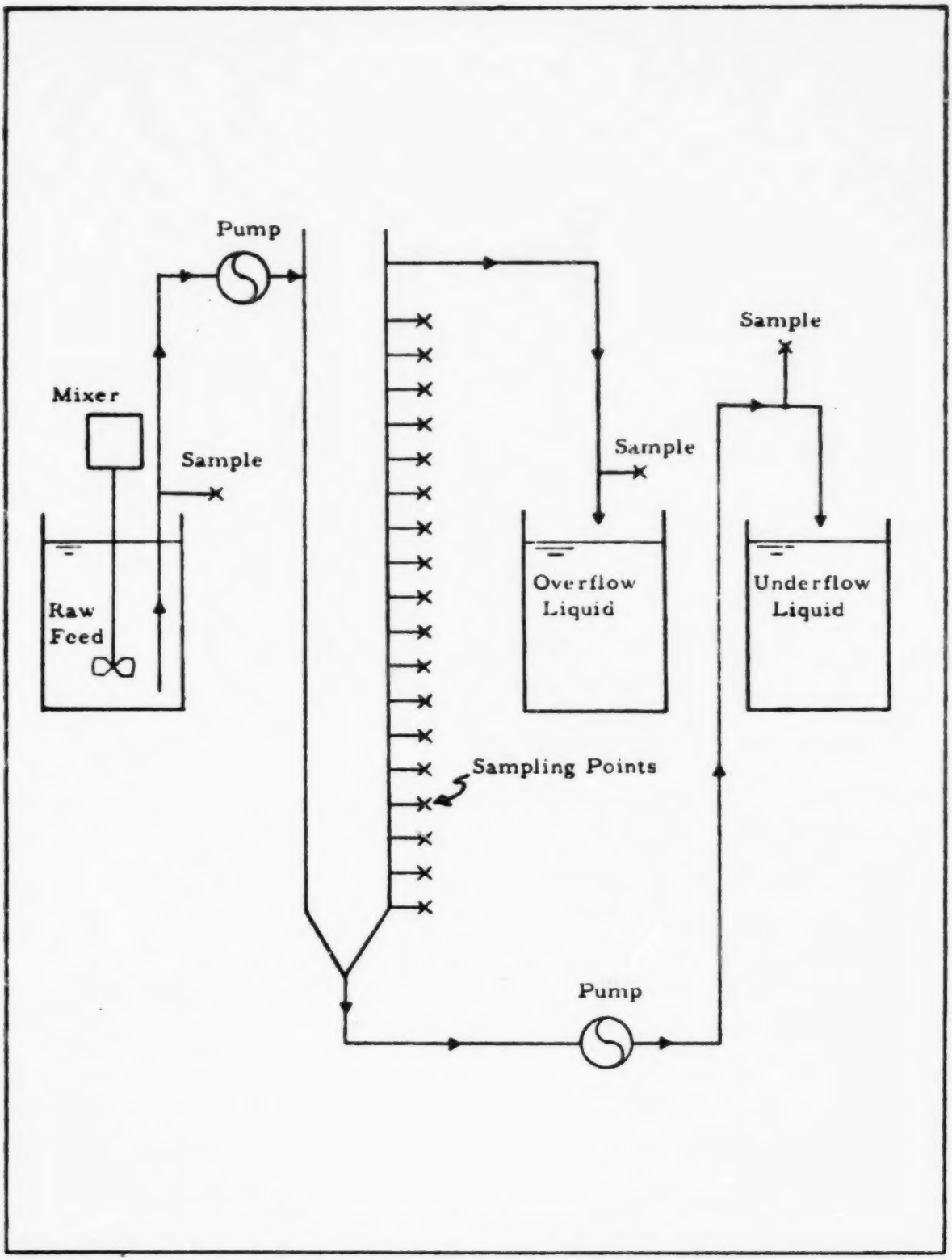


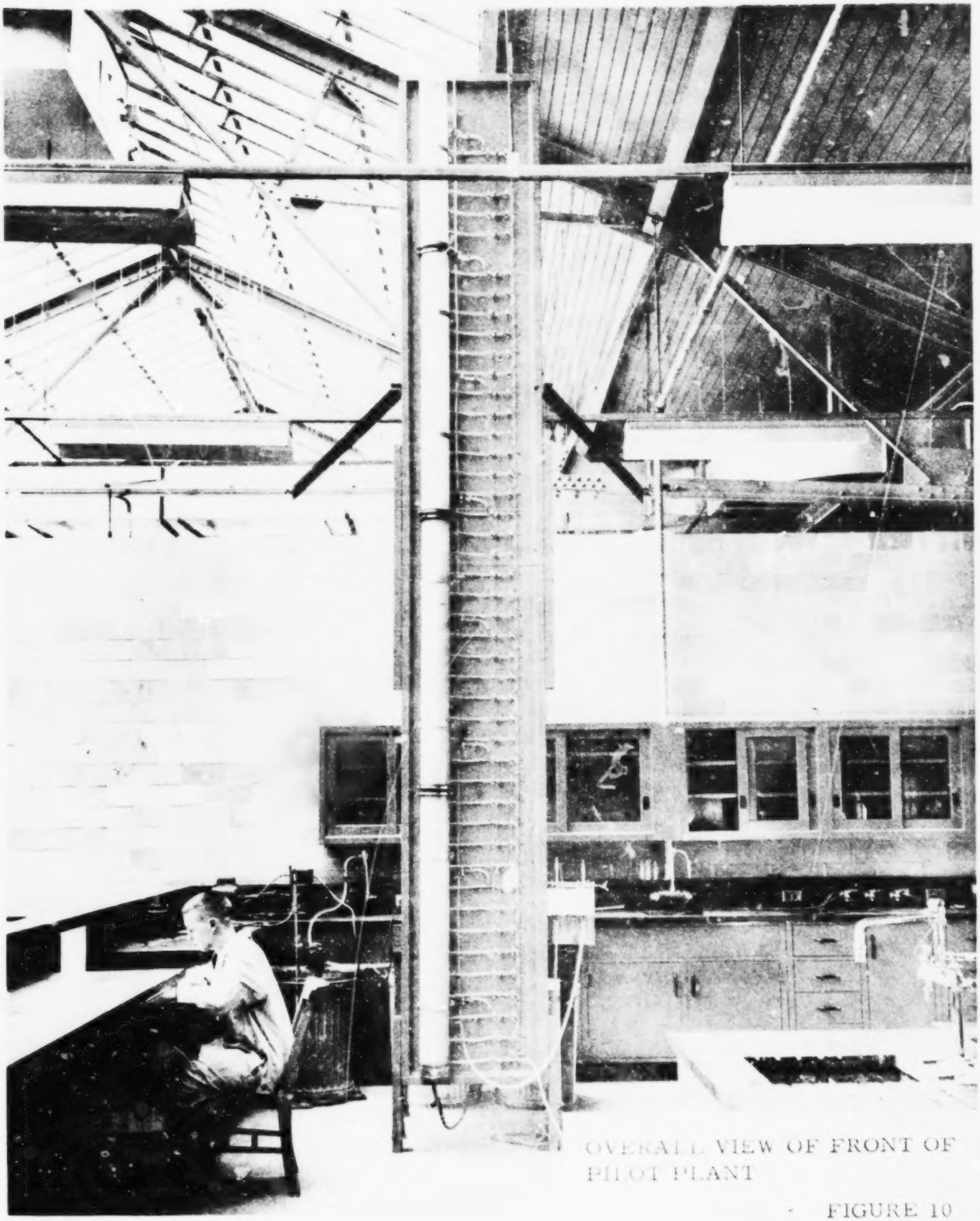
FIG. 9 SCHEMATIC FLOW DIAGRAM OF THICKENING PILOT PLANT

An overall view of the front of the pilot plant is shown in the photograph in Figure 10 and a close up view showing the sampling taps and the pressure micrometer gage is shown in Figure 11. A view of the back of the pilot plant showing the sigmamotor pumps and the inlet and outlet arrangement is shown in Figure 12.

b. Operation Procedures

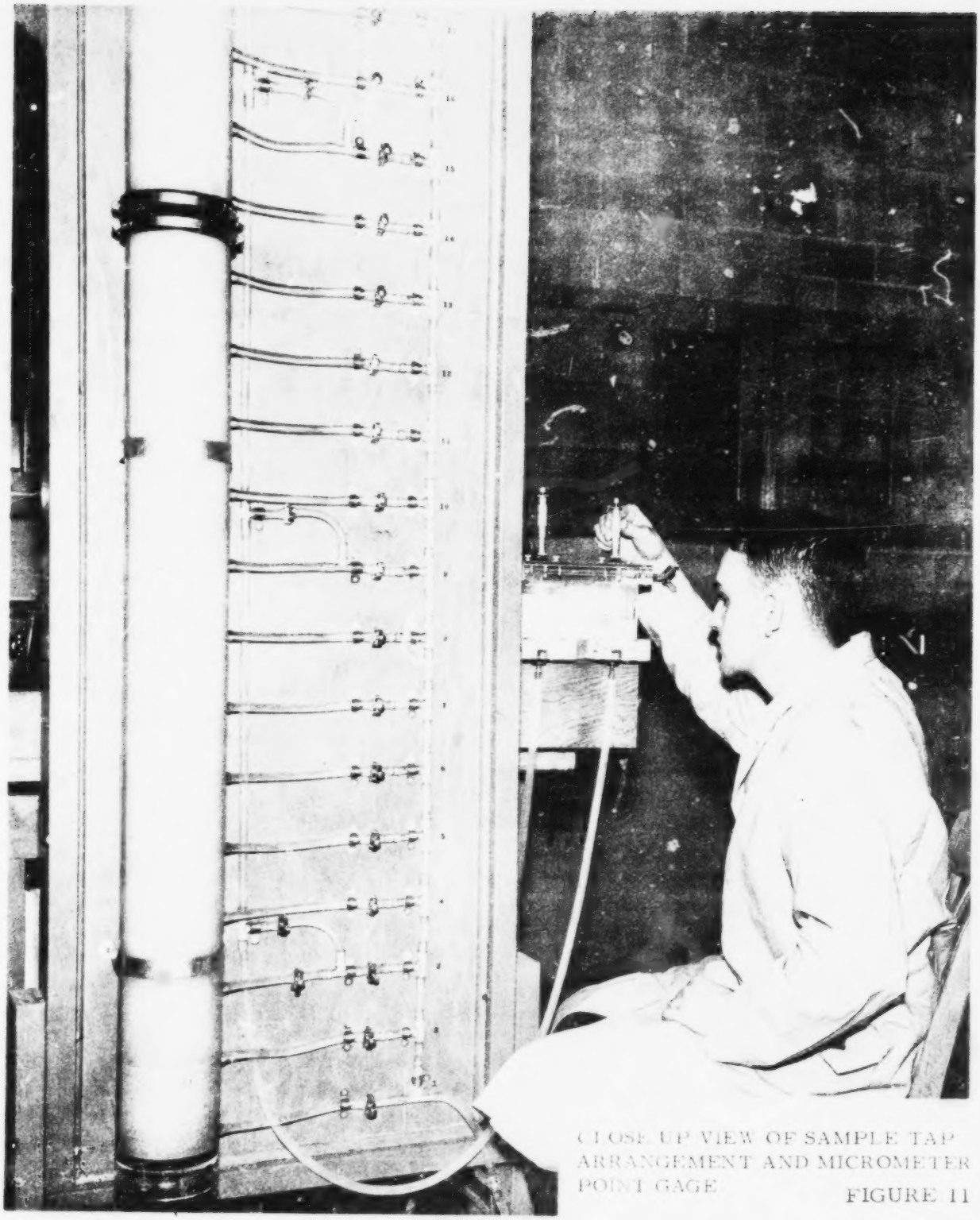
Routine operating procedures were set up for pilot plant operation such that the design loading conditions in each test could be maintained at a nearly constant level and to insure that each test was carried to the point of steady state conditions. Using the sigmamotor pumps there was no problem of maintaining constant flow rates in the raw feed, underflow and overflow. Using the synthetic liquid solids mixtures such as calcium carbonate slurries the raw feed solids concentration could be maintained quite constant at any desired level, however, when actual waste sludges were used it was difficult in many cases to accurately control the raw feed concentration at a constant level during a test run.

In all of the continuous flow pilot plant tests it was considered essential that each test be continued to a point of steady state or equilibration before any meaningful analysis of its performance could be made. Some of the problems of earlier tests on continuous flow thickening stemmed from the fact that the tests were discontinued before steady state conditions were established. It was necessary therefore in the present investigations to establish criteria which could be used to indicate when the thickening unit had reached steady state performance under the selected loading conditions. The criteria established for this purpose in the tests was the solids balance and steady state conditions were assumed to have been reached when there was a balance of the weight of solids "in" and "out" of the thickening unit. In preliminary tests it was found that the time required to reach equilibrium varied with the conditions tested. In most



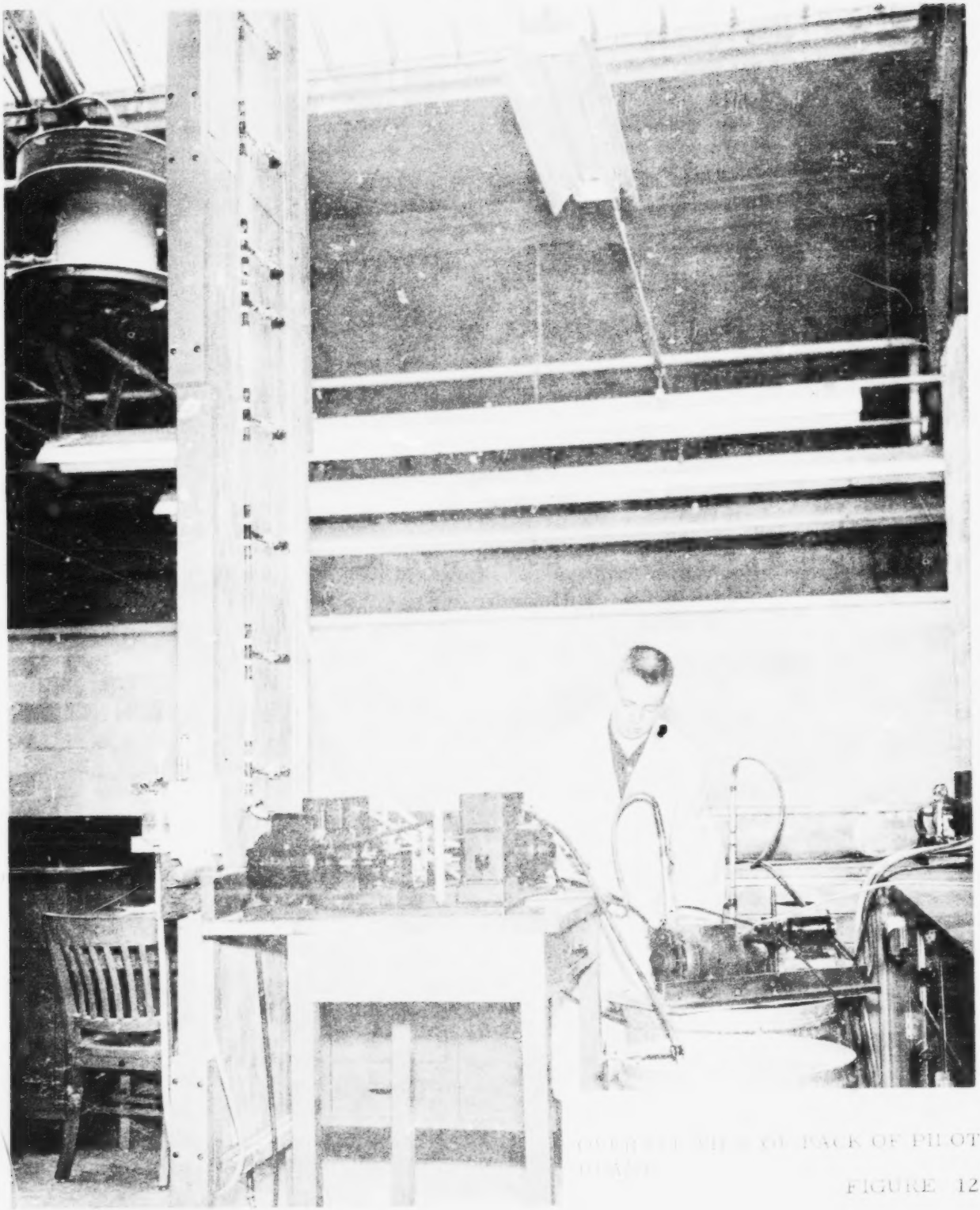
OVERALL VIEW OF FRONT OF PILOT PLANT

FIGURE 10



CLOSE UP VIEW OF SAMPLE TAP ARRANGEMENT AND MICROMETER POINT GAGE

FIGURE 11



OVERALL VIEW OF BACK OF PILOT HOUSE

FIGURE 12

of the investigations reported herein the minimum time between starting the pilot plant at a selected set of loading conditions and sampling was 24 hours. If an analysis of the data did not indicate a reasonable solids balance, the test results were discarded or the test was rerun for a longer period of time. In those situations where variable plant run sludges were being tested in the pilot plant it is possible that steady state conditions were never reached even though a solids balance was achieved.

When it was considered that the pilot plant was operating under steady state conditions, the loading and performance were established by measuring the flow rates and solids concentrations of the raw feed, underflow, and overflow and also measuring the depth and solids gradient in the sludge blanket.

2. Experimental Batch Test Procedures

The experimental procedures used in conducting the batch settling tests in these investigations were quite simple. Preliminary tests indicated that wall effects would be negligible for tube diameters in excess of 1.5 inches. During the first year tests on synthetic liquid-solids mixtures, standard 250 ml graduated cylinders (1.6" diameter) were used as settling containers and in the tests on actual waste sludges standard one liter graduated cylinders (2.5 inches diameter) were used. In general, a batch settling test was conducted for each pilot plant test since it was found that especially in the case of actual waste sludges, the settling characteristics of the material would vary from day to day. Except in the case of the synthetic suspensions where each batch test included five to ten dilutions (these results were presented in Progress Report 145 S) the batch settling tests were conducted on the same solids concentration that was being fed to the pilot plant and on several dilutions of this suspension. The dilutions were made by adding relatively clear supernatant to the original suspension. At time zero each of the samples was carefully mixed to avoid air entrainment and insure a uniform initial solids concentration in the tube. Starting

at time zero the fall of the liquid solids interface was observed at two minute intervals for 10 minutes, 5 minute intervals to 30 minutes, 10 minute intervals to 60 minutes and then at 20 minute intervals for several hours. In all cases except one test on calcium carbonate slurry the tests were conducted at room temperature.

D. INVESTIGATIONS ON CALCIUM CARBONATE SLURRIES

1. General

The program of investigations on the factors affecting thickening were initiated on inert synthetic liquid-solids mixtures (as distinguished from organic and biological sludges) during the first year of research. A number of preliminary batch and pilot plant tests were conducted using various flocculent and non flocculent solids in order to select a mixture which would remain constant and give reproducible results. Based on the results of these tests it was decided to use slurries of powdered calcium carbonate in the initial phase of the research program on thickening. (The results of the investigations carried out during the first year of research have been presented in Progress Report No. 145 S dated January 1, 1962.) These studies included an extensive series of batch and pilot plant tests on powdered calcium carbonate slurries. The results of these tests will be reviewed briefly in this report and re-evaluated in terms of a method developed for relating the data obtained in batch tests to continuous flow situations.

2. Characteristics of Powdered Calcium Carbonate Slurries

The batch and continuous flow test series conducted during the program were carried out on slurries of powdered calcium carbonate diluted to various degrees with Minneapolis city tap water. A commercial grade of powdered calcium carbonate designated as Type G Whiting as manufactured by the Calcium Carbonate Co. of Chicago, Illinois was used in all of the tests. The physical and chemical properties of this material as supplied by the manufacturer are given in Table 1. The sieve analyses and particle size distribution were verified in the laboratory and indicated that in a dry state 99% + of the particles fell in a range of 1 to 25 microns. When mixed with water the material did not appear to flocculate to a large extent on visual observation. However, under microscopic examination

TABLE 1

Physical and Chemical Properties
of G Whiting Powdered
Calcium Carbonate

Physical Properties

	Quincy G
Screen Analysis (Cum. % Thru)	
100 Mesh 0.0058 in. opening	99.999%
200 Mesh 0.0029 in. opening	99.998
325 Mesh 0.0017 in. opening	99.985
Micron Size Distribution	
Plus 25 Microns	5.5
10 to 25 Microns	24.5
5 to 10 Microns	25.1
1 to 5 Microns	35.4
Minus 1 Micron	9.5
Specific Gravity - Absolute	2.72

Chemical Properties

	Percent
Moisture	0.0600
Calcium Carbonate	97.3600
Magnesium Oxide	0.7100
Silica	0.6400
Ferric Oxide	0.1600
Aluminum Oxide	0.2900
Titanium Oxide	0.0014
Manganese Oxide	0.0300
Tri-Calcium Phosphate	0.0440
Sulphur	0.0500
Calcium Oxide (Combined with Silica)	0.0100
Magnesium Oxide (Combined with Silica)	0.0200
Acid Insoluble Organic Matter	0.0600
Arsenic - 0.3 ppts. per million	
	99.4354

it was evident that the particles did agglomerate into groups of particles which ranged in size from 50 to 500 microns and averaged about 200 microns. The absolute specific gravity of the particles was measured periodically during the tests and averaged 2.75 as compared to 2.72 reported by the manufacturer.

3. Experimental Results on Powdered Calcium Carbonate

a. General

The experimental procedures used in conducting the batch tests and pilot plant tests on calcium carbonate slurries were the same as outlined earlier in this report. A large number of preliminary batch tests were carried out while the pilot plant was being built and tested. The actual test series on calcium carbonate slurries however, was carried out by conducting batch tests and pilot plant tests concurrently. The results of these tests will be reviewed in terms of the method described earlier for analyzing batch test results for determining the limiting capacity of continuous flow thickeners and to determine the practical loading parameters which affect the performance of continuous flow thickeners.

b. Results of Batch Tests

The preliminary batch tests on calcium carbonate slurries were conducted to determine if reproducible results could be obtained using various dilutions of powdered calcium carbonate and water. In each test a series of ten dilutions were made ranging from a low concentration of 20 grams of calcium carbonate per liter to a high concentration of 400 grams per liter. The results of these tests were analyzed by both the Kynch method and the Coe and Clevenger method to determine V as a function of C for the liquid solids interface and develop the characteristic

batch flux curve. From these preliminary tests which have been discussed in detail in Progress Report 145 S it was found that at a particular temperature the settling characteristics of calcium carbonate slurries remained quite constant. Also because of the difficulty of determining the initial interface velocity especially at lower concentrations the Kynch method of analysis gave more consistent results than that of Coe and Clevenger. Further, it was found that if the maximum bottom concentrations (C_u) were approximated by the method described earlier, the value varied from about 50% at low initial solids concentration (2.0%) to about 70% at the highest concentrations (40%). This would indicate that for this relatively nonflocculent material the increased depth and weight of solids above the bottom at the higher concentrations caused an increase in the ultimate bottom concentration. It should be pointed out however that similar tests on the flocculent water plant sludge, sewage sludge, anaerobic sludge and activated sludge did not show this effect and in fact with the active biological sludges the reverse situation appeared to be true.

A large volume of data has been taken on batch settling tests that were run concurrently with the pilot plant tests on calcium carbonate slurries. For this reason it would probably be most efficient to illustrate the application of batch test results to continuous flow thickening using the data from one typical test as an example.

The batch flux curve and the interface and bottom solids concentrations shown in Figures 13 and 14 have been computed by the Kynch method as described earlier from the results of an actual settling test conducted on the raw feed suspension used in pilot plant test No. E-9. There are two important characteristics of this suspension that might be used in predicting the limiting capacity of a continuous flow thickener that can be noted from this batch test analysis. First, the limiting batch flux or loading appears to be in the neighborhood of 400 lb/sq ft/day. It should be pointed out at this point however that it is difficult to accurately establish

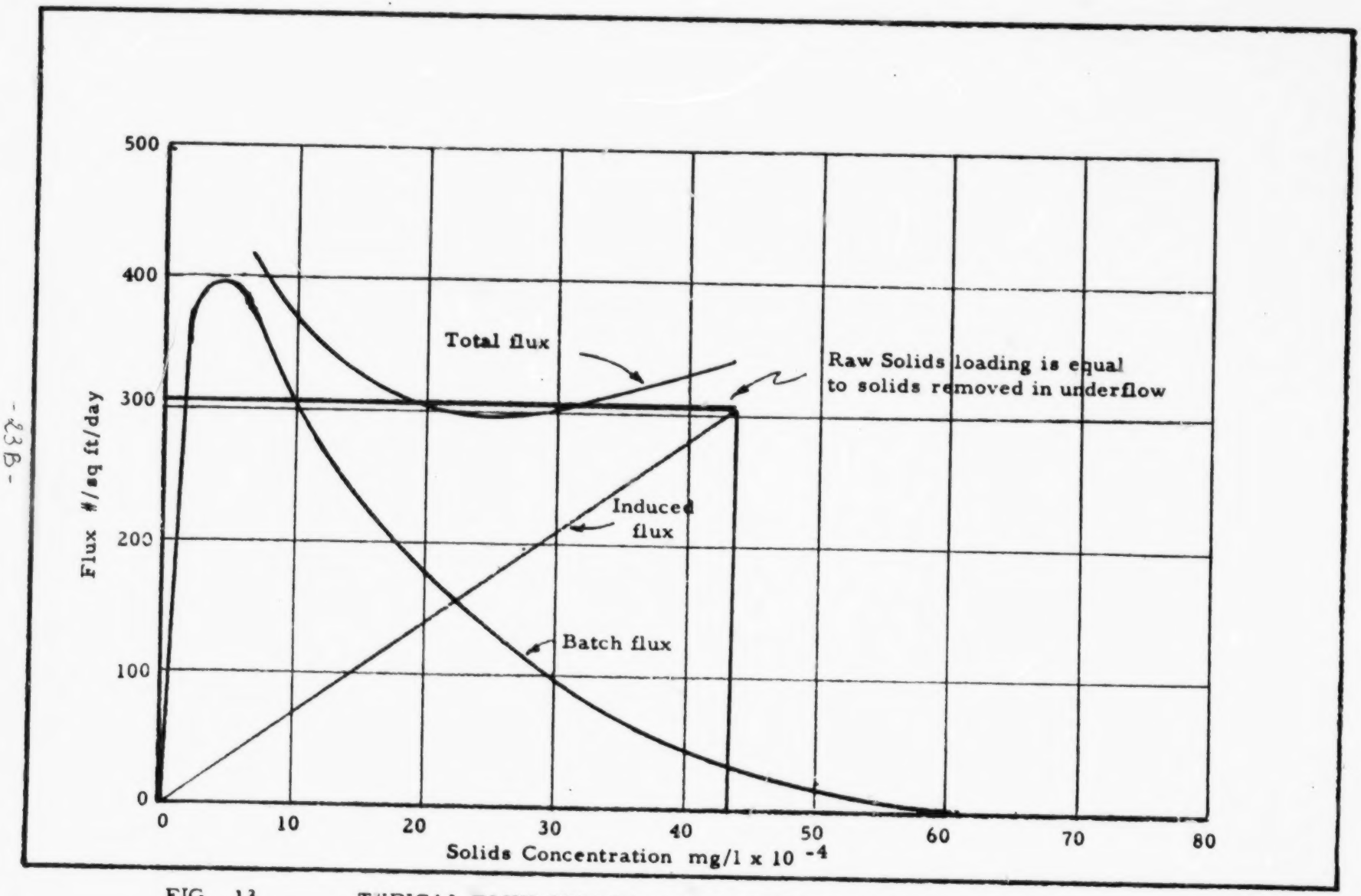


FIG. 13 TYPICAL FLUX CURVES FOR CALCIUM CARBONATE SLURRIES FOR PILOT PLANT TEST E-9

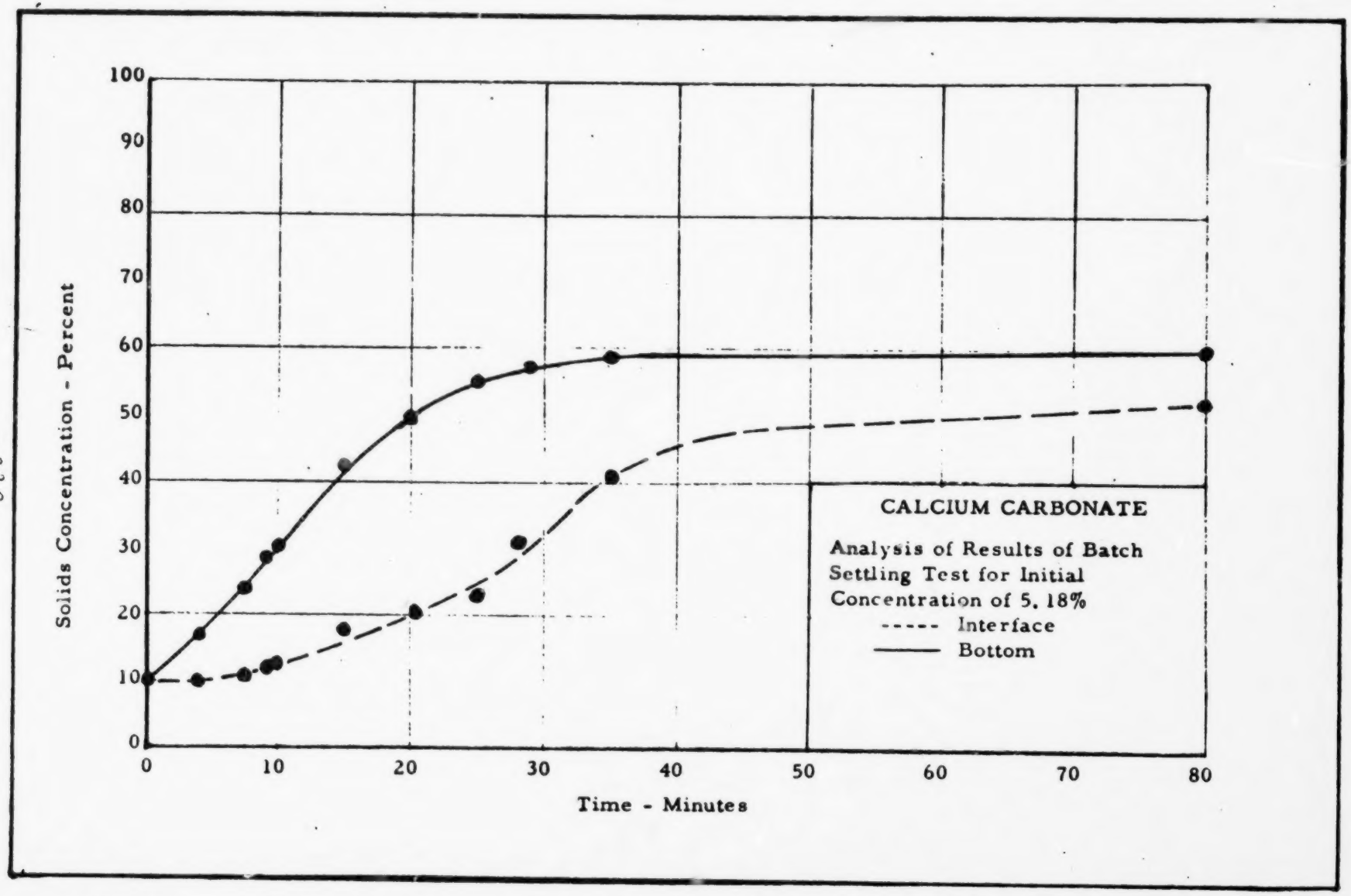


FIG. 14 EFFECT OF SETTLING TIME ON INTERFACE AND BOTTOM SOLIDS CONCENTRATION FOR BATCH TESTS TAKEN DURING PILOT PLANT TEST E - 9

this maximum point because at these low solids concentrations the liquid solids interface is not well defined and the shape of the flux curve below this point is somewhat meaningless. In fact, as will be seen later, with flocculent suspensions in many cases this maximum batch flux point cannot be determined from batch tests. The second characteristic that is noted from this batch data is that the limiting concentration (C_u = 60%) is reached in about 40 minutes after which there is very little increase in concentration. From these batch test results we would predict a limiting solids loading of about 400 lb/sq ft/day with a limiting concentration index of 60.0% in a continuous flow thickener in order to prevent solids loss in the overflow. The other batch test results that were run during the pilot plant tests on calcium carbonate slurries indicated similar results with the exception that using raw feed solids concentrations of about 2.0% the limiting loading appeared to be near 300 lb/sq ft/day and limiting concentration index about 50.0%.

Figure 15 shows the solids concentration gradient in the sludge blanket for pilot plant test E-9. The four zones of concentration as described earlier are evident. In attempting to explain the reasons for these zones the balanced loading conditions showing the induced flux in the underflow and the total flux for the continuous flow conditions of test E-9 are shown in Figure 13. A possible explanation of the solids concentration in each zone could be made as follows. Since the thickener is not overloaded (no solids in overflow) the raw feed entering at 5% solids is diluted to about 2.5% which can pass more than the 305 lb/sq ft/day raw feed loading. This would leave a clear zone above the inlet and an inlet zone with a constant concentration of 2.5%. As the influence of the restriction of the bottom is reached where the solids must increase to the discharge concentration it is noted that the total flux curve is below the loading curve between solids concentrations of 20 to 30%. For this reason an intermediate zone is formed where the solids increase abruptly from 2.5% to 30%. Finally in a narrow zone at the bottom the concentration

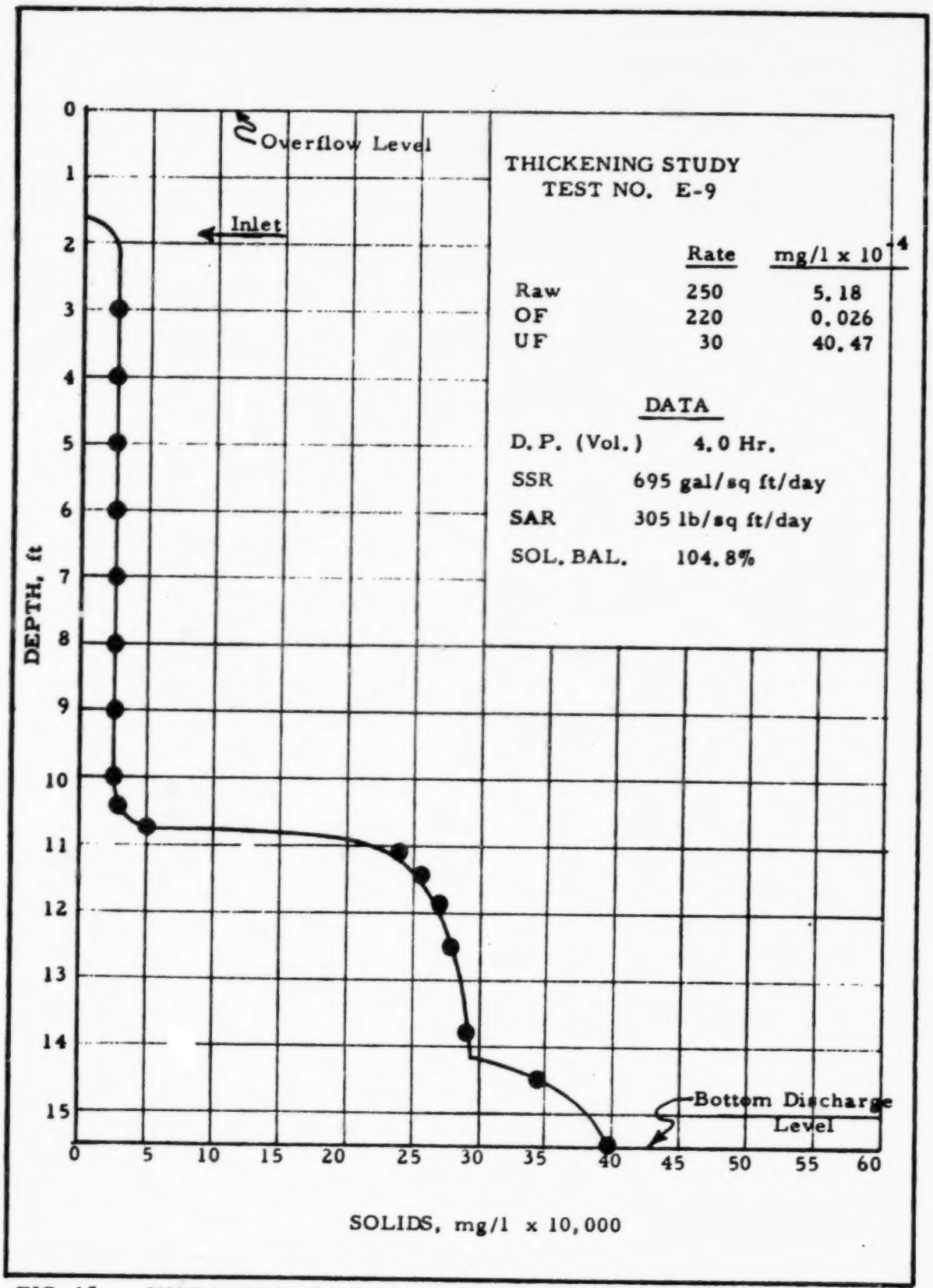


FIG. 15 SUSPENDED SOLIDS GRADIENT IN SLUDGE BLANKET FOR PILOT PLANT TEST E-9

increases quite sharply to a discharge concentration of about 43%. This explanation is a matter of conjecture and during these investigations the factors affecting the depths of the bottom zone and intermediate zone have not been established.

c. Results of Pilot Plant Tests

A summary of the results of the pilot plant tests on calcium carbonate slurries is shown in Table 2. The only tests included in this summary are those which showed a solids balance within $\pm$ 10%. An explanation of the headings in the tables are as follows.

1. Flow ratio = $\frac{Q_R}{Q_{UF}}$

2. Susp. Sol. = suspended solids
   Raw = raw feed
   O. F. = overflow
   U. F. = underflow

3. Solids balance = $\frac{\text{wt. of solid in}}{\text{wt. of solids out}}$

4. Det. Per. = detention period based on raw flow, hrs.

5. SSR = raw flow surface settling rate, gal/sq ft/day

6. SAR = solids applied rate, # solids/sq ft/day

7. Flow ratio x SAR = $\frac{Q_R}{Q_{UF}}$ x SAR

8. Concentration index = $\frac{Q_R}{Q_{UF}}$ x C_R

9. Sol. Rem. % = $\frac{\text{wt. solids in underflow}}{\text{wt. solids in raw feed}}$ x 100

10. Sludge depth ft - total depth of sludge in thickening unit which is at a greater solids concentration than the raw feed concentration

TABLE 2

SUMMARY - PILOT PLANT THICKENING EXPERIMENTS
CALCIUM CARBONATE SLURRY

Test No.	Flow Ratio	Susp. Sol. mg/l x 10^{-4} Raw	O.F.	U.F.	Solids Bal %	Det. Per. Hrs	SSR -	SAR +	Flow Ratio x SAR	Conc. Index gm/l	Sol Rem %	Sludge Depth ft
A-P	10.21	2.49	0.050	26.12	95.7	2.6	970	223	2277	254.2	98.19	0.5
A-1	10.25	7.72	5.268	32.00	97.5	2.5	1125	730	7483	791.3	38.50	15.5
A-4	9.71	5.07	1.030	35.87	109.5	2.7	1050	445	4321	492.3	81.80	15.5
A-5	9.21	3.53	0.026	34.47	93.9	2.6	1060	316	2910	325.1	99.34	0.7
B-1	6.82	2.83	0.021	20.45	94.0	2.0	1375	326	2223	193.0	99.37	0.3
B-2	12.57	2.94	0.018	38.41	99.4	4.2	660	163	2049	369.6	99.44	0.5
B-3	13.10	1.87	0.018	24.70	99.3	4.1	690	108	1415	245.0	99.11	0.4
B-4	6.73	1.78	0.027	11.15	106.0	2.0	1400	207	1393	119.8	98.71	0.5
B-5	6.67	2.91	0.019	19.26	101.0	4.1	680	166	1107	194.1	99.45	0.3
B-6	13.02	2.68	0.027	34.89	100.0	2.0	1375	305	3971	348.9	99.07	1.6
B-7	6.52	1.76	0.037	11.70	97.0	4.1	690	101	659	114.8	98.22	0.5
B-8	13.64	1.93	0.026	26.17	100.0	1.9	1400	226	3083	263.3	98.75	0.5
D-1	17.30	3.67	1.061	49.22	95.0	2.5	1100	338	5847	634.9	72.6	11.3
D-2	10.00	1.77	0.012	18.72	94.5	5.0	550	82	820	177.0	99.39	0.4
D-3	5.00	3.94	0.104	21.05	92.0	5.0	550	182	910	197.0	97.90	0.6
D-5	10.00	4.67	0.026	46.50	100.0	5.0	550	216	2160	467.0	99.50	0.7
D-6	5.58	1.62	0.021	9.27	98.0	5.0	550	76	424	90.4	98.94	0.4
E-1	16.62	2.66	0.034	44.49	99.0	2.2	1250	277	4604	442.1	98.80	1.1
E-2	13.75	2.65	0.023	36.95	99.0	2.3	1200	270	3713	364.4	99.20	0.5
E-3	21.23	2.89	0.027	55.22	108.0	2.3	1225	298	6327	613.5	99.08	1.9
E-4	7.62	5.49	0.030	44.84	93.4	4.5	610	280	2134	418.3	99.50	1.9
E-5	6.87	5.53	0.026	36.21	103.0	4.5	600	280	1924	379.9	99.60	1.0
E-6	9.90	6.17	0.042	56.12	106.4	4.6	595	310	3069	610.8	99.39	3.2
E-7	8.84	5.40	0.012	47.13	102.0	4.5	610	276	2440	477.4	99.80	1.3
E-9	8.33	5.18	0.026	40.47	104.8	4.0	695	305	2540	431.5	99.56	4.7
E-9A	8.83	5.33	0.030	44.46	99.0	4.0	695	308	2566	444.0	99.50	6.3
E-11	9.04	5.41	0.025	54.43	91.7	5.0	550	249	2251	489.1	99.59	2.1
E-14	9.33	5.51	0.052	55.44	92.6	5.1	540	250	2333	514.1	99.16	1.1
E-15	9.52	5.22	0.028	51.52	98.0	4.5	600	265	2523	496.9	99.52	1.4
E-16	9.14	5.31	0.032	47.98	102.0	4.1	685	305	2788	485.3	99.46	2.5

A preliminary analysis of all of these various loading parameters on the performance of the thickener in terms of solids removal and sludge depth indicated that the only loading parameters which had a measurable and significant effect on performance were the solids applied rate and the concentration index. For this reason the analysis of pilot plant data in the remainder of this report will be based on the effect of those two variables.

For the continuous flow pilot plant tests on calcium carbonate slurries the effect of the solids applied rate on the sludge depth and the percent solids removal is shown in Figures 16 and 17. It is apparent for these tests that the loading range tested was for the most part less than the capacity of the thickener. However, the data indicate quite clearly that the limiting loading to avoid solids loss in the overflow is about 300 to 350 lb/sq ft/day. It is also evident that the sludge depth increases quite abruptly at this limiting load.

The effect of the concentration index on sludge depth and solids removal is shown in Figures 18 and 19. Although the data are a bit more scattered with regard to the effect of the concentration index it appears that the limiting index to prevent solids overflow is between 500 and 600 grams/liter (50 to 60%). A check of the data indicates that the tests which indicate the higher limiting index are for tests which had the highest solids concentration in the raw feed. These results based on the continuous flow pilot plant tests indicate that for raw feed solids concentrations of about 2.0 to 5.0% the limiting solids applied load is about 300 lb/sq ft/day at a concentration index of 50 to 60% and these values are fairly close to those predicted from the batch settling tests.

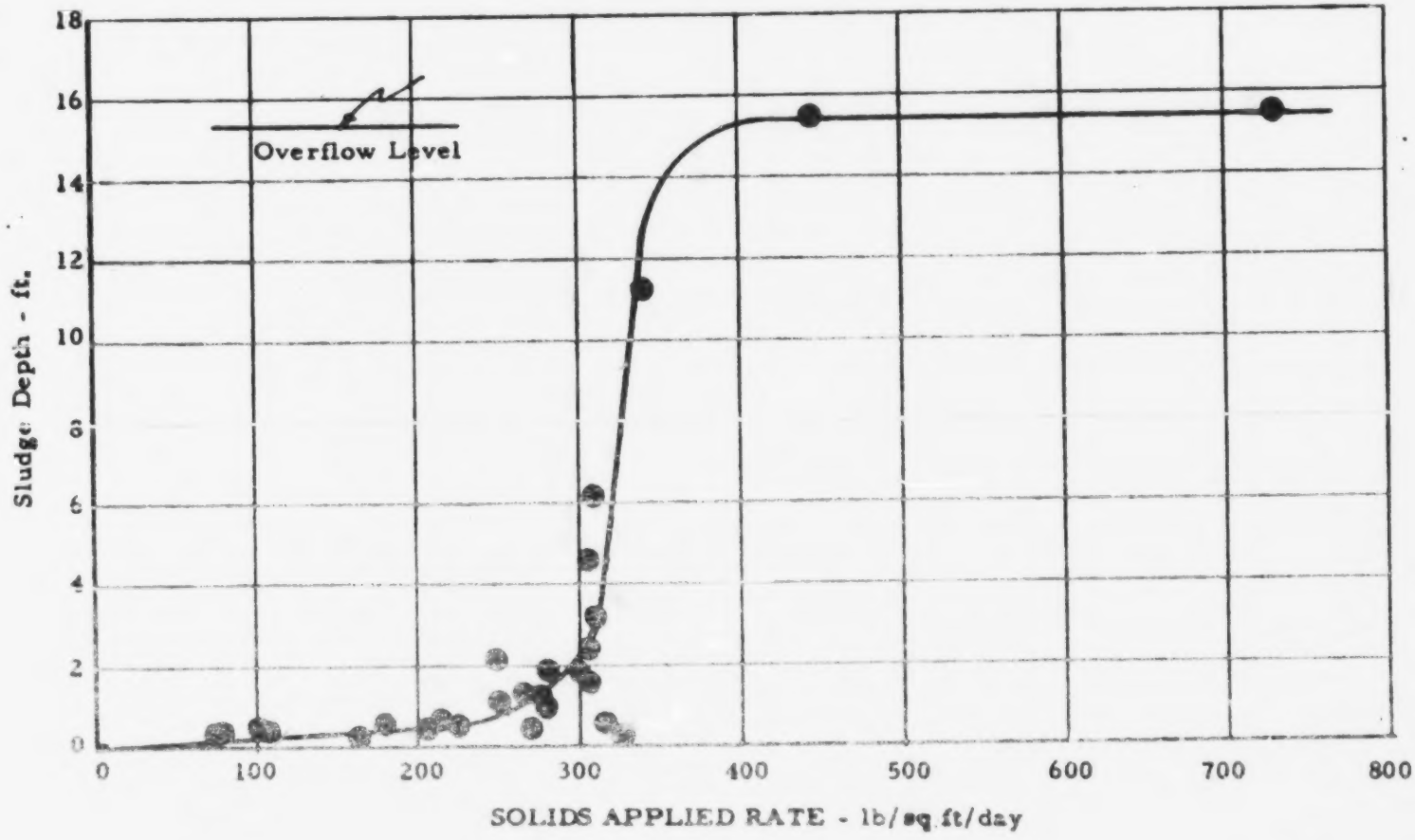


FIG. 16 EFFECT OF SOLIDS APPLIED RATE ON SLUDGE DEPTH FOR CALCIUM CARBONATE SLURRY

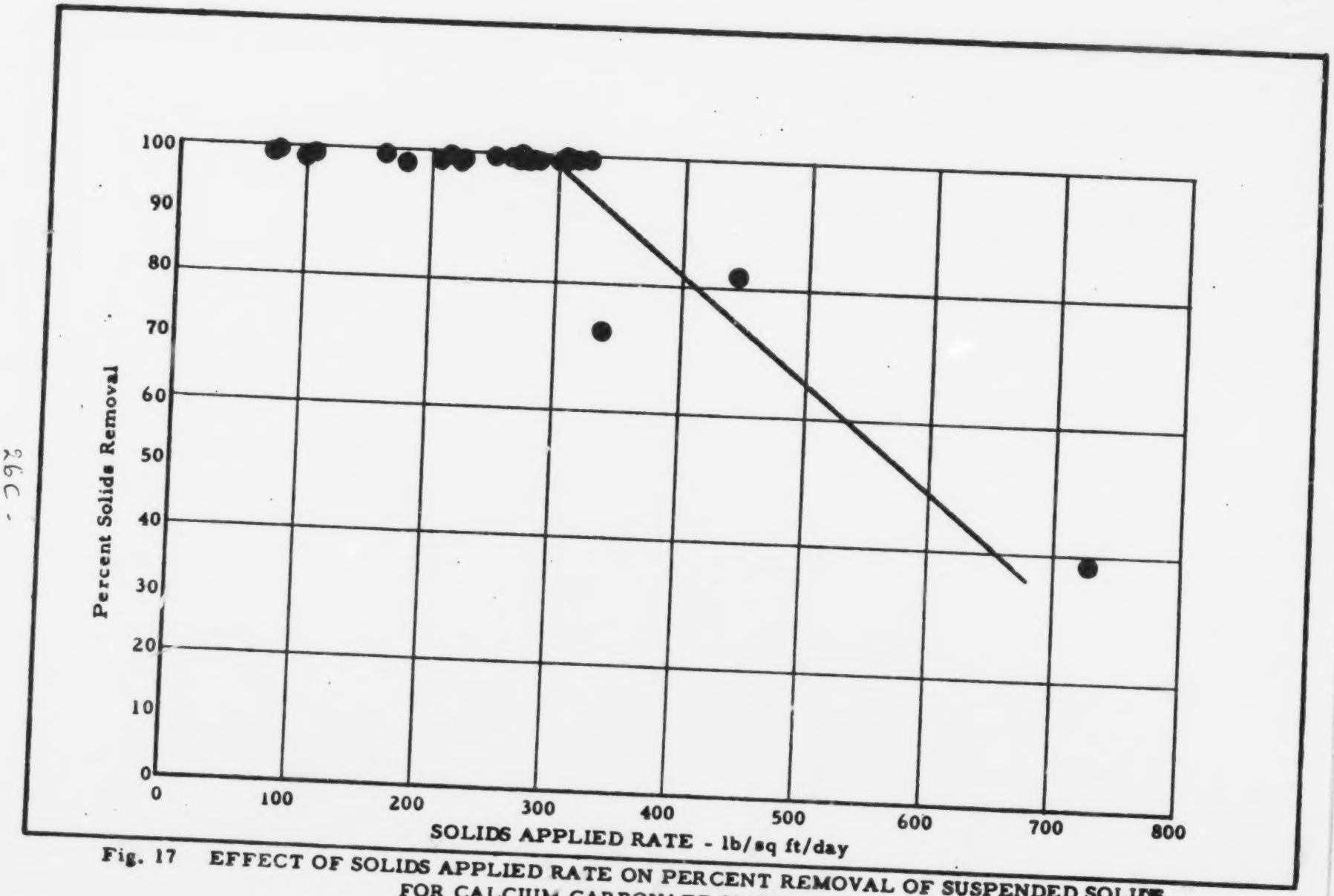


Fig. 17 EFFECT OF SOLIDS APPLIED RATE ON PERCENT REMOVAL OF SUSPENDED SOLIDS FOR CALCIUM CARBONATE SLURRY

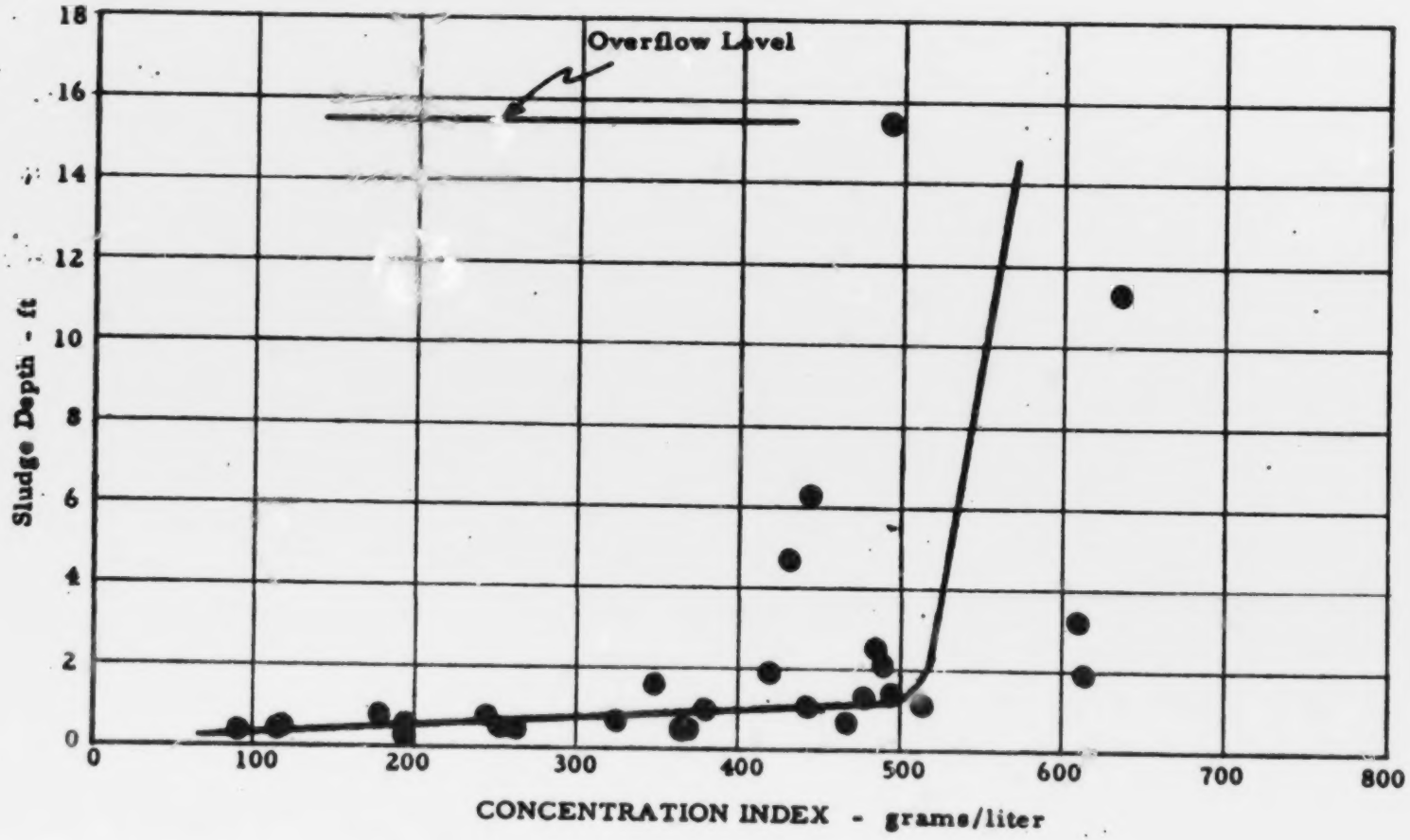


Fig. 18 EFFECT OF CONCENTRATION INDEX ON SLUDGE DEPTH FOR POWDERED CALCIUM CARBONATE SLURRY

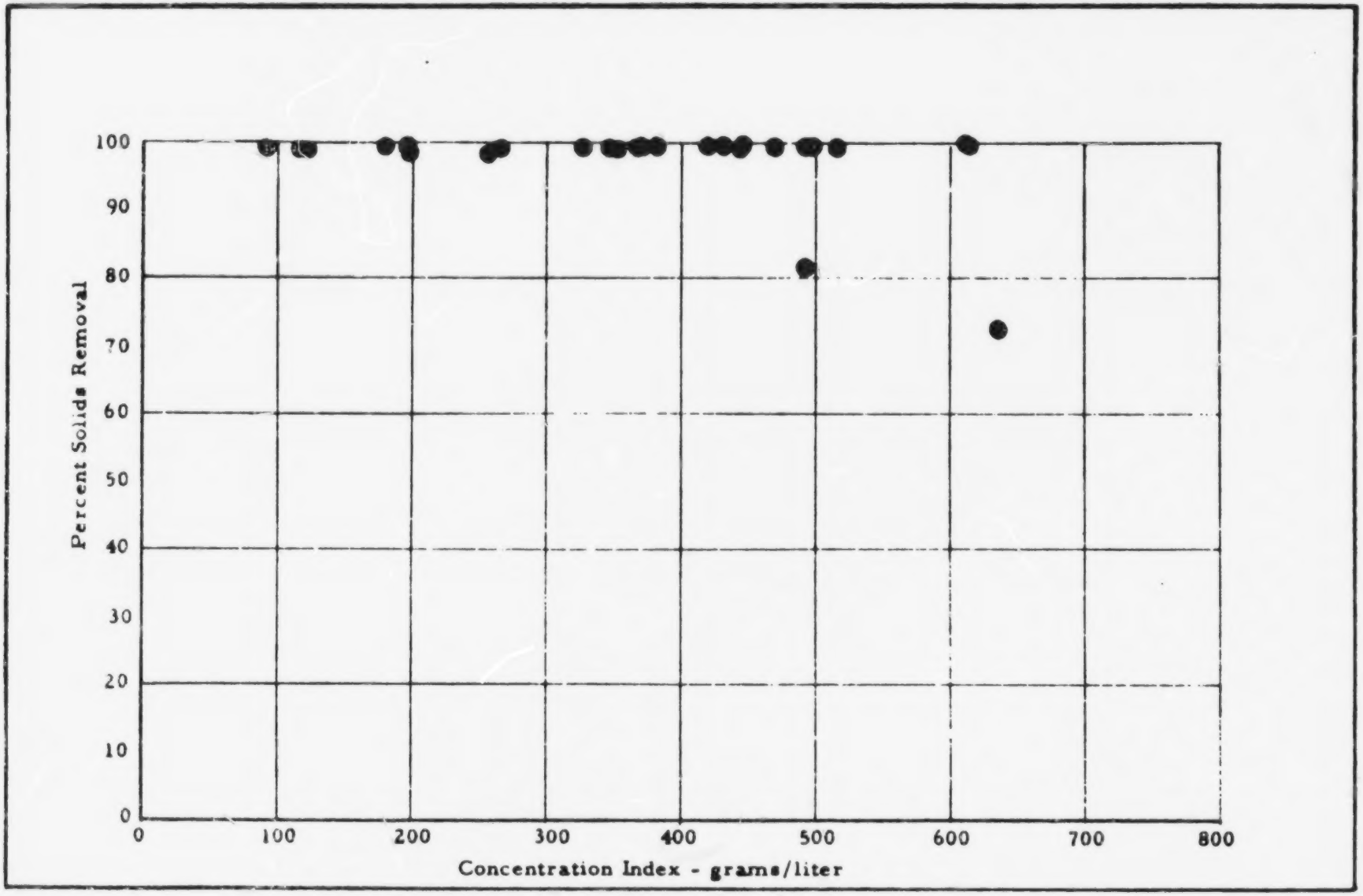


Fig. 19 EFFECT OF CONCENTRATION INDEX ON PERCENT SOLIDS REMOVAL FOR POWDERED CALCIUM CARBONATE SLURRY

E. INVESTIGATIONS ON WATER SOFTENING SLUDGE

1. General

A series of batch and pilot plant tests were carried out on sludge obtained from the Minneapolis water softening plant. These tests were carried out in a continuous flow thickener which was being operated under a different research project conducted by the University of Minnesota for the Minneapolis Water Department. The data from these tests has been reevaluated in terms of the batch test analysis and new loading parameters developed in the present investigations and will be included in this report.

2. Characteristics of Water Softening Sludge

The water softening sludge used in these investigations was taken directly from the Spaulding precipitators at the Minneapolis lime softening plant. The solids in the sludge were mainly precipitated calcium carbonate and a small percentage of magnesium hydroxide. The appearance of the sludge as it was fed to the thickening unit was very flocculent with a "floc" particle size of 1/16 to 1/8 inch. The average dry specific gravity of the solids was 2.64.

3. Experimental Results on Water Softening Sludge

a. General

The experimental procedure used in conducting the batch tests on water softening sludge was the same as outlined earlier. The pilot plant tests however were carried out in a 36 inch diameter concrete tube 17 feet deep. The operating routine however was similar to that used on our laboratory scale pilot plants.

b. Results of Batch Tests

Batch tests were run concurrently with each of the pilot plant tests using the same solids concentration as was being fed to the continuous thickening unit. During the test series the settling characteristics of the sludge as indicated by the results of the batch tests did not appear to vary a great deal. Again, the results of a typical batch test will be used to illustrate the application of batch test results to predict the limiting capacity of the continuous flow thickener. The batch flux curve and the interface and bottom concentrations have been computed for the batch test taken during pilot plant test No. 6 and are shown in Figures [illegible] and [illegible] respectively. This data indicates that a limiting load of about 175 lb/sq ft/day at a limiting solids concentration (C_u) of about 6.0 to 7.0%. The loading conditions of the pilot plant during test No. 6 have been applied to Figure 20 to develop the total flux curve and the solids concentration gradient in the pilot plant is shown in Figure 22. The solids loading of 227 lb/sq ft/day and the concentration index of 11.0 during this test are both above the limits predicted from the batch test analysis and would indicate solids loss in the overflow. This is shown to be true as is indicated in Figure 20.

c. Results of Pilot Plant Tests

A summary of results of the 12 pilot plant tests that were conducted on water softening sludge is shown in Table 3. For these tests the effect of solids applied load on sludge depth and solids removal is shown in Figures 23 and 24. These results indicate a limiting solids applied load of about 150 lb/sq ft/day. The effect of concentration index on sludge depth and solids removal are shown in Figures 25 and 26 and indicate a limiting concentration index of about 60 or 70 grams per liter (6.0 to 7.0%). These limiting loadings are quite close to those predicated from the batch settling tests that were run during the pilot plant investigations.

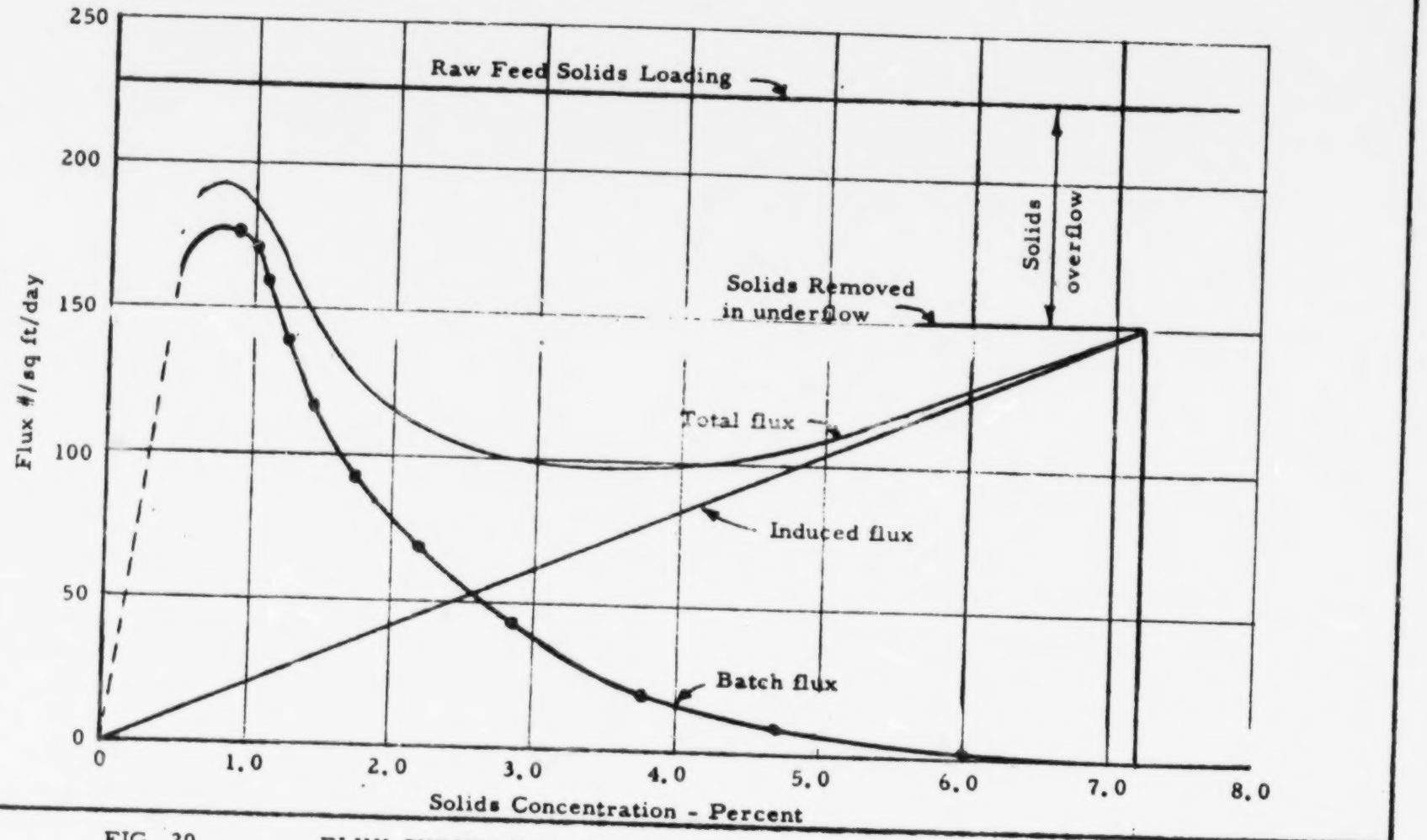


FIG. 20 FLUX CURVES FOR PILOT PLANT TEST NO. 6

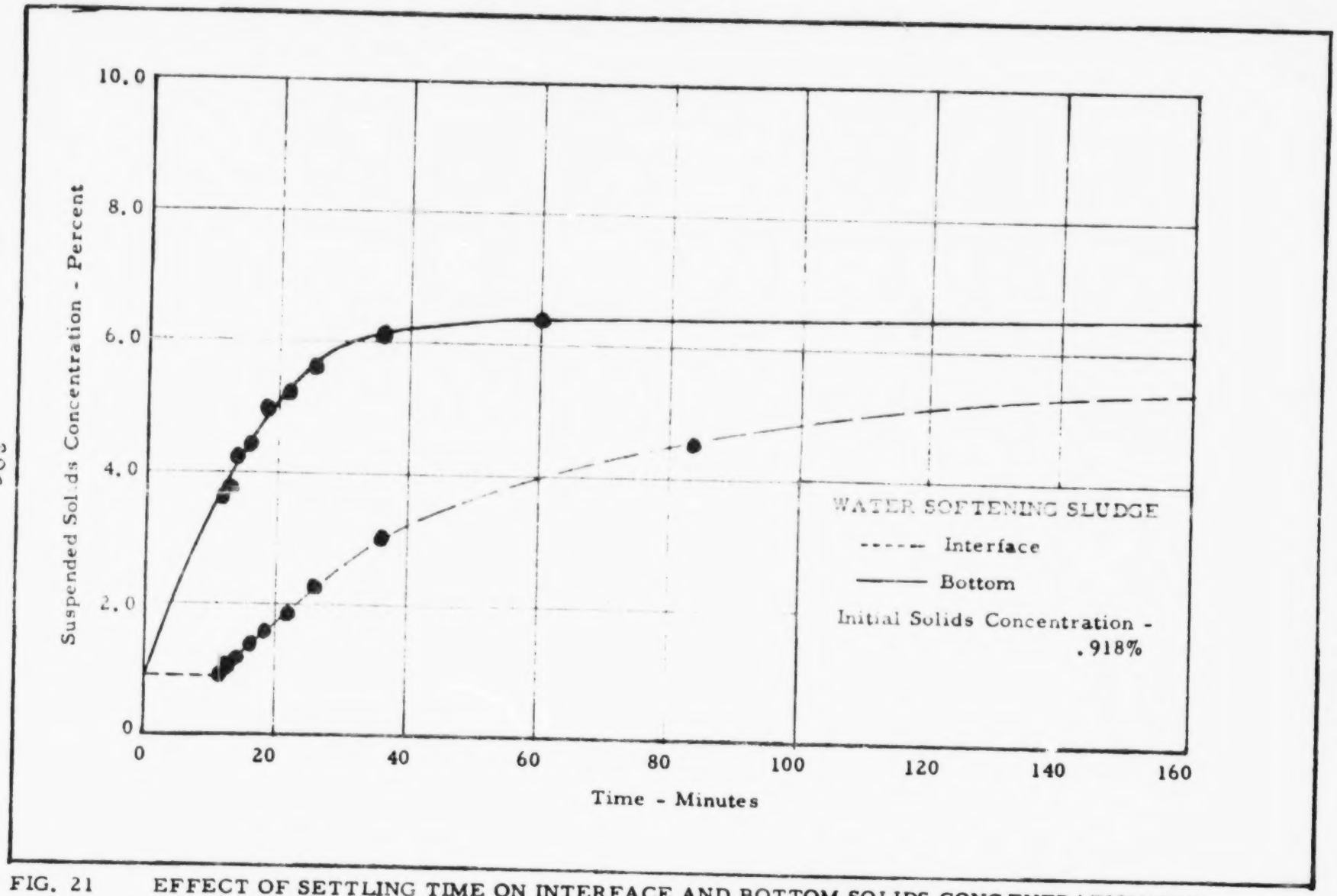


FIG. 21 EFFECT OF SETTLING TIME ON INTERFACE AND BOTTOM SOLIDS CONCENTRATION FOR BATCH TESTS TAKEN DURING PILOT PLANT TEST NO.. 6

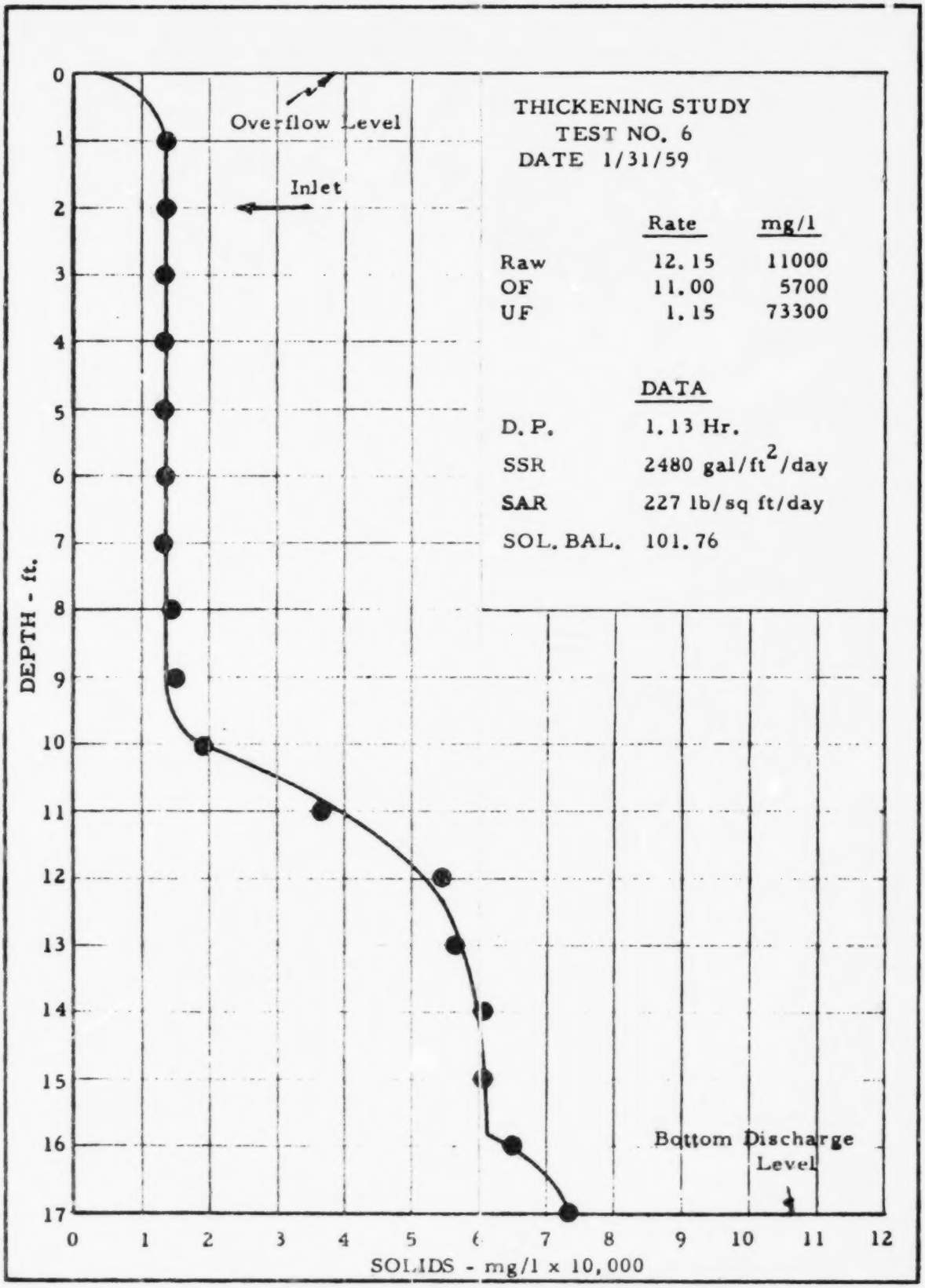


FIG. 22 SUSPENDED SOLIDS GRADIENT DIAGRAM IN SLUDGE BLANKET FOR PILOT PLANT TEST NO. 6

TABLE 3

SUMMARY - PILOT PLANT THICKENING EXPERIMENTS
WATER SOFTENING SLUDGE

Test No.	Flow Ratio	Susp. Sol - % Raw	O.F.	U.F.	Solids Bal %	Det Per Hrs.	SSR *	SAR *	Flow Ratio x SAR	Conc. Index gm/l	Sol. Rem %	Sludge Depth ft.
1	5.29	0.84	0.00	4.47	114	1.53	1830	128	677	44.44	100	3.0
2	5.88	1.10	0.16	5.69	109	1.37	2040	187	1099	64.68	88	16.5
3	17.70	1.18	0.70	8.16	111	1.10	2525	248	4390	208.86	39	17.0
4	5.28	0.63	0.00	3.80	114	1.71	1635	86	454	33.26	100	2.0
5	10.00	0.62	0.00	6.86	110	1.37	2040	105	1050	62.00	100	6.5
6	12.15	1.10	0.57	7.33	101	1.13	2480	227	2758	133.65	55	17.0
7	17.00	1.26	0.94	10.91	118	1.61	1732	182	3094	214.20	51	17.0
8	6.75	0.97	0.00	6.71	102	1.37	2040	165	1114	65.48	100	12.5
9	4.71	1.61	0.92	5.07	111	1.71	1631	219	1031	75.83	67	17.0
10	15.80	1.61	1.25	8.87	107	1.37	2040	274	4329	254.40	34	17.0
11	10.00	1.74	1.15	6.39	96	1.14	2450	356	3560	174.00	37	17.0
12	9.98	1.05	0.43	6.63	100	1.15	2440	214	2136	104.79	60	16.5

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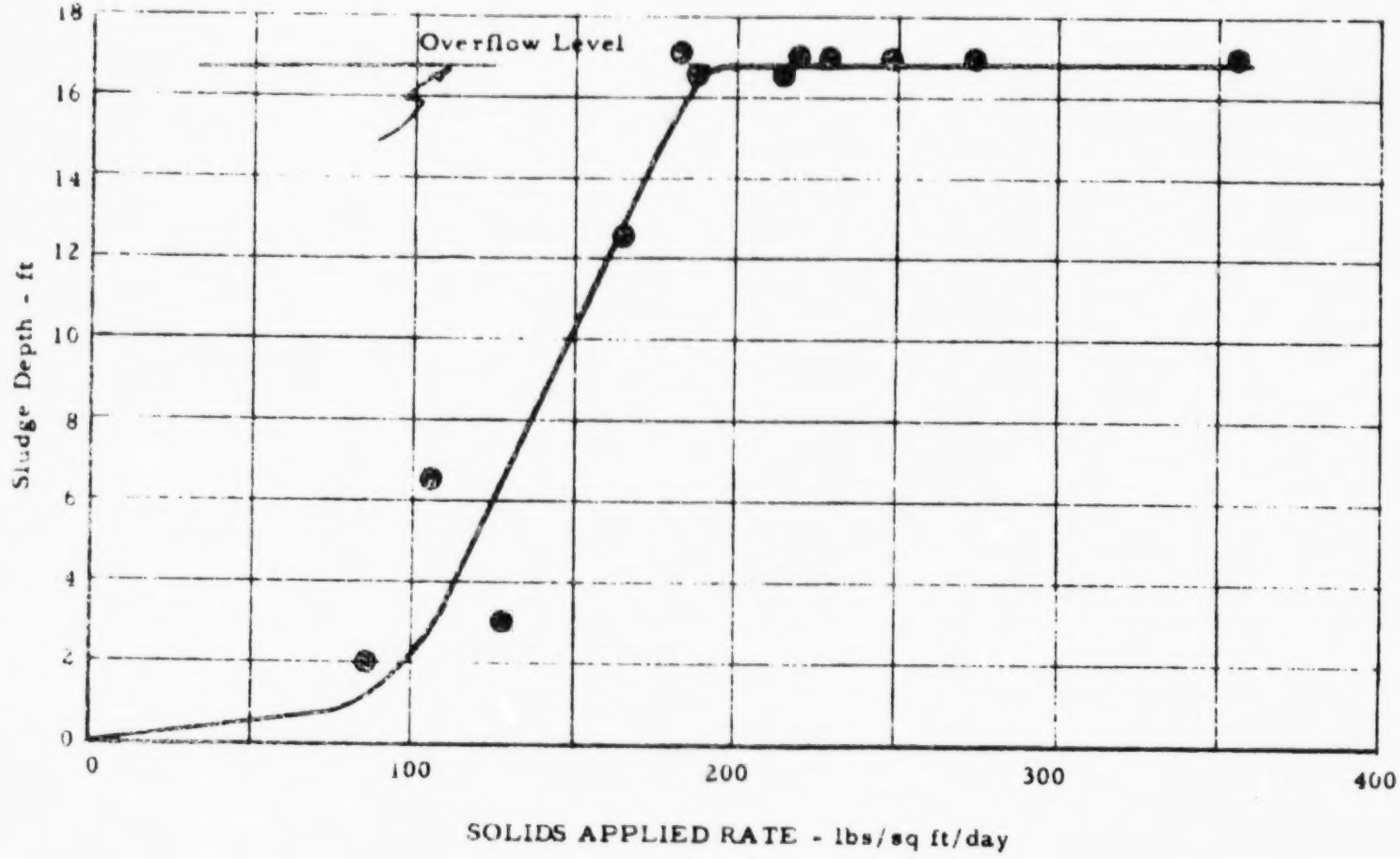

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Fig. 23 EFFECT OF SOLIDS APPLIED RATE ON SLUDGE DEPTH FOR WATER SOFTENING SLUDGE

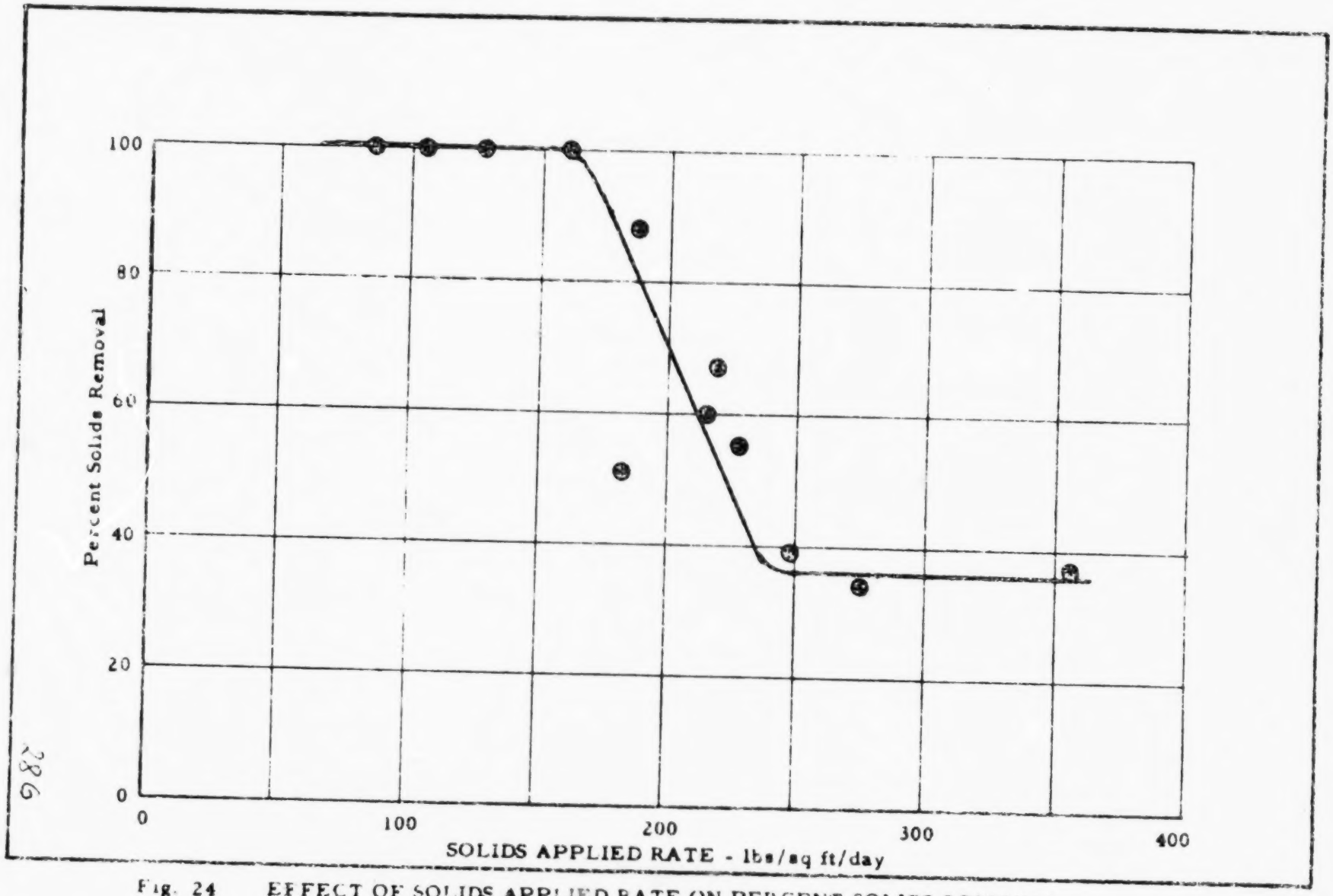

Fig. 24 EFFECT OF SOLIDS APPLIED RATE ON PERCENT SOLIDS REMOVAL FOR WATER SOFTENING SLUDGE

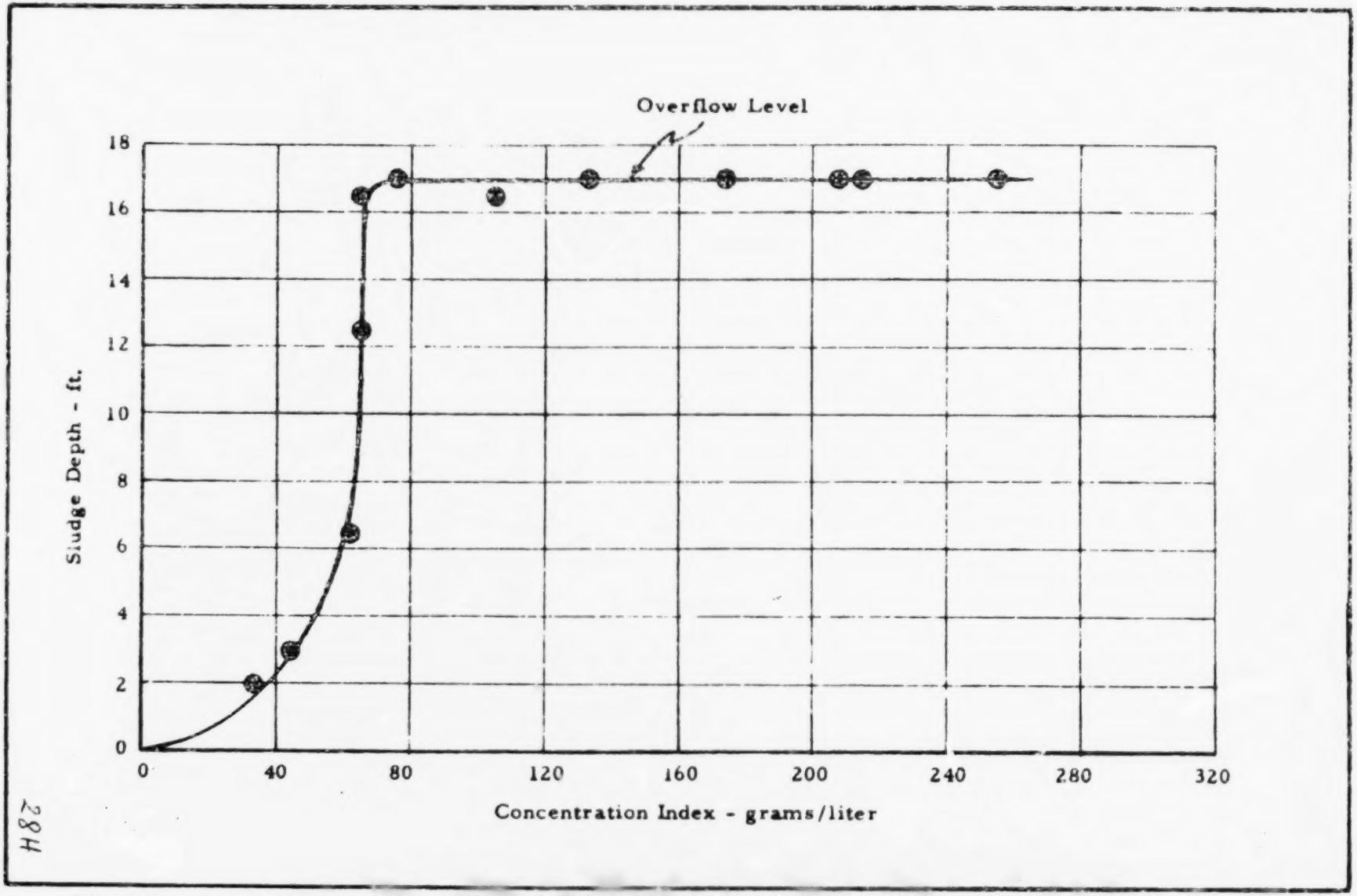

Fig. 25 EFFECT OF CONCENTRATION INDEX ON SLUDGE DEPTH FOR WATER SOFTENING SLUDGE

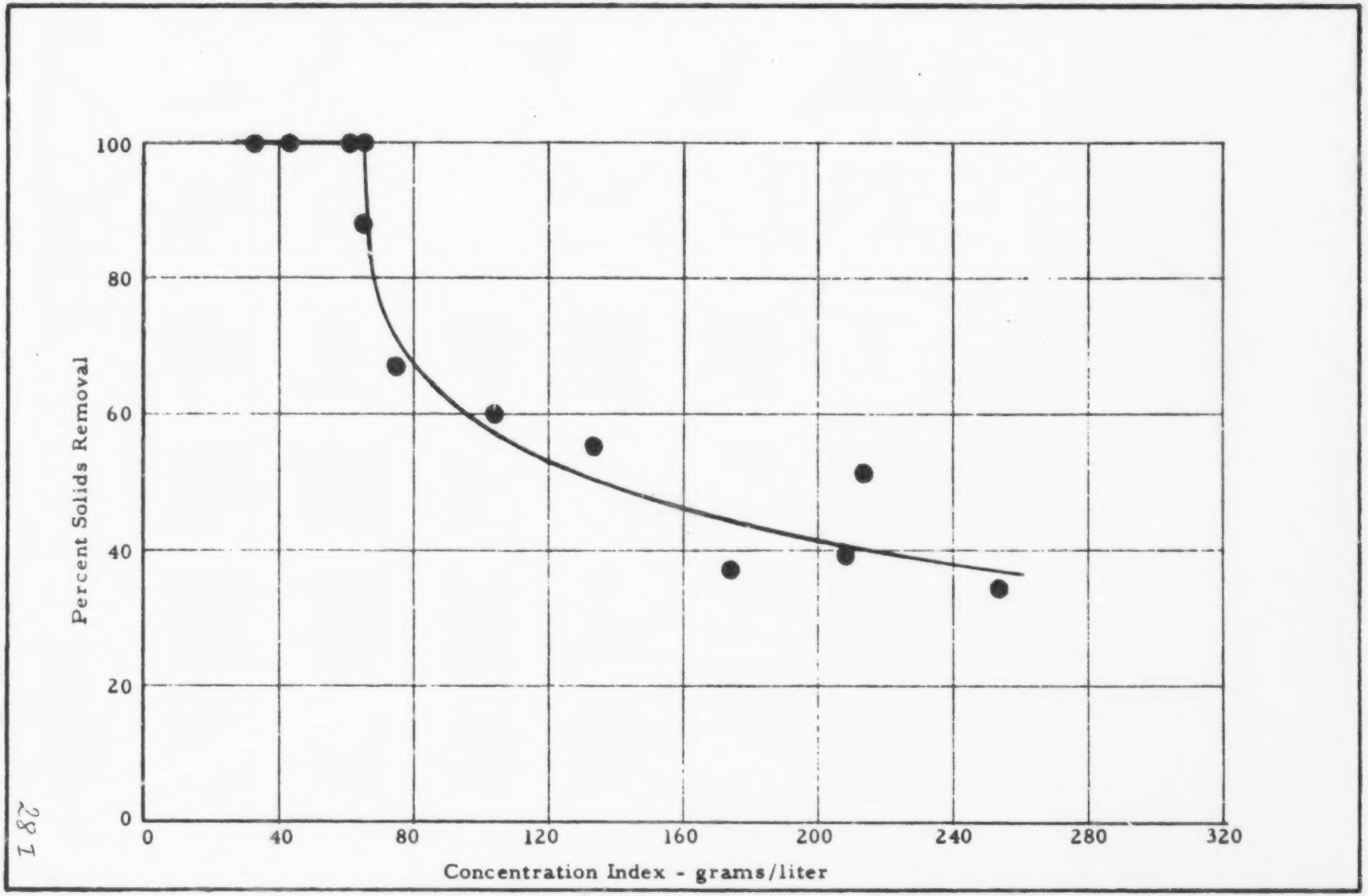

Fig. 26 EFFECT OF CONCENTRATION INDEX ON PERCENT SOLIDS REMOVAL FOR WATER SOFTENING SLUDGE

F. INVESTIGATIONS OF AERATED SUPERNATANT SLUDGE

1. General

A series of batch and continuous flow pilot plant tests were conducted at the Minneapolis and St. Paul Sanitary District Sewage Plant on the supernatant sludge from the primary sludge thickening tanks. Experiments were being conducted under another research project to determine if aerobic digestion of the supernatant sludge would reduce the BOD and flocculate the solids before returning it to the primary tank influent. This aerobically digested material is denoted aerated supernatant sludge in this action. During the investigations on thickening, the raw feed was taken from the effluent end of the experimental sludge aerobic digestion tanks which provided a detention period of about 7 days.

2. Characteristics of Aerated Supernatant Sludge

Since the aerated supernatant sludge contained some large sized solids which would tend to block the 1/2 inch feed lines in the pilot plant thickener, the raw feed suction was provided with a screen with 1/8" openings. Even with this arrangement considerable difficulty was experienced with blocked lines, especially in the underflow. The aerated sludge appeared quite flocculant and was dark brown in color. The solids concentration of the aerated sludge varied from day to day but was generally in the range of .5 to 1.1% suspended solids. It was noted from the batch tests that the supernatant liquid contained quite a bit of dark colloidal material (1000 to 1500 ppm) which would not settle out. Also it was apparent from the settling tests that the settling characteristics of the sludge changed quite markedly during the test period. This was indicated by a progressive increase in the 30 min sludge volume index, from 25

ml/gram at the beginning of the tests to 80 ml per gram at the end of the test period. The sludge also contained quite a lot of fibrous material and was biologically active. In the pilot plant tests especially at long detention periods, clear liquid pockets and gas bubbles were noted in the sludge blanket. The dry specific gravity of the solids varied from 1.3 to 1.8 and averaged about 1.5. In general it was difficult to get good pilot plant results with this sludge because of its variable and unstable nature. Blocked lines and mechanical failures also made it difficult to maintain steady state conditions in the tests.

3. Experimental Results on Aerated Supernatant Sludge

a. General

The experimental procedures used in conducting the batch tests and pilot plant studies on aerated supernatant sludge was the same as outlined earlier. One exception was that the material was screened and the solids concentrations were computed to exclude the colloidal material that would not settle out. Also, because the solids concentrations varied during the tests, the raw feed concentration was based on the average concentration at the beginning and end of each test.

b. Results of Batch Tests

As in the other test series, batch tests were run concurrently with each of the pilot plant tests using the same material that was being fed to the continuous thickening unit. The test series included over 30 individual tests but because of mechanical failures, line blockages and the difficulty of establishing a solids balance and steady state conditions in the pilot plant tests, only 11 tests were considered meaningful. An analysis of the results of a batch test taken during pilot plant test S-4 will be used as an example. The batch flux curve and the bottom and interface concentrations have been computed and are shown in Figures 27 and 28.

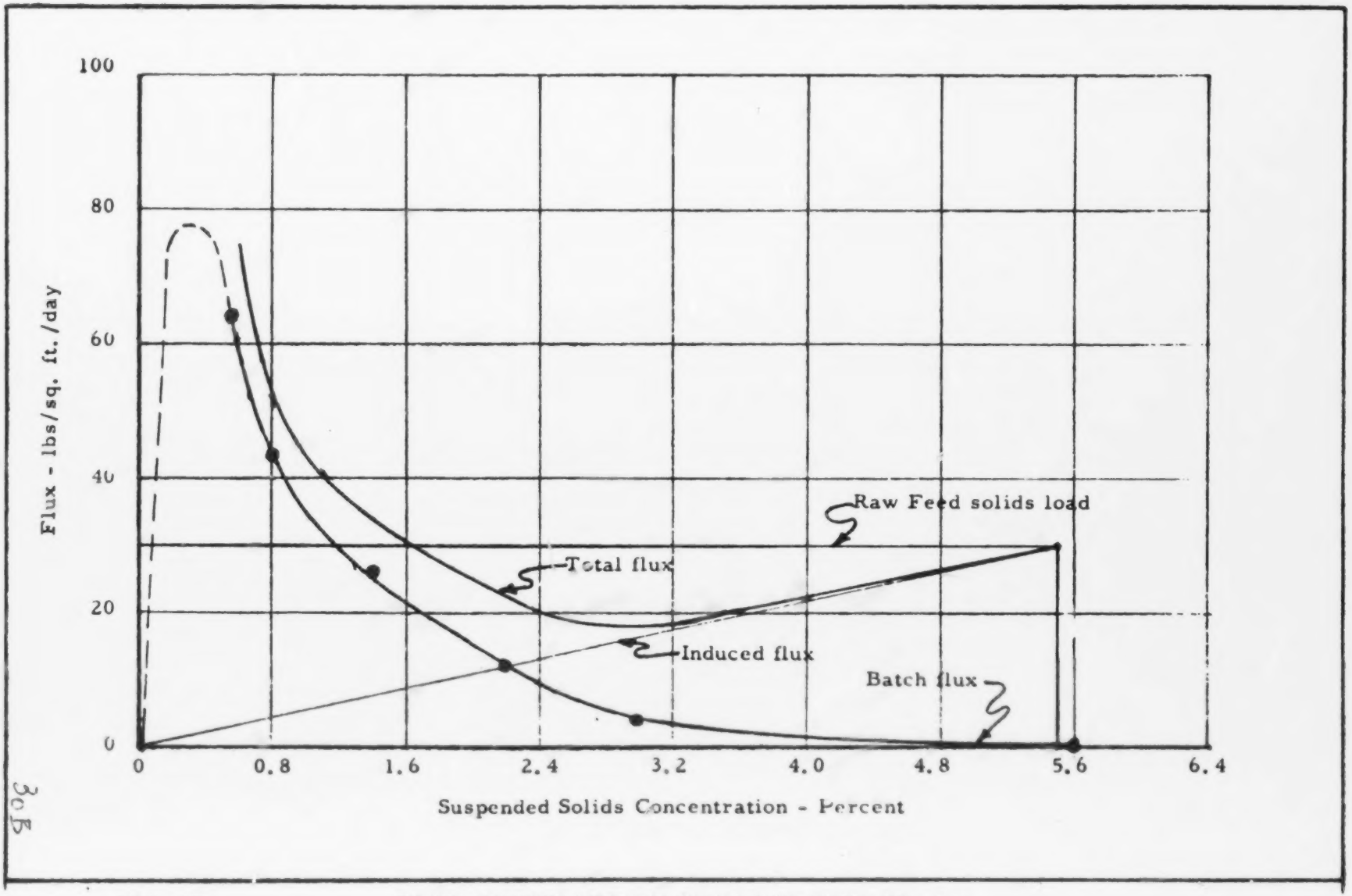

FIG. 27 FLUX CURVES FOR PILOT PLANT TEST NO. S-4

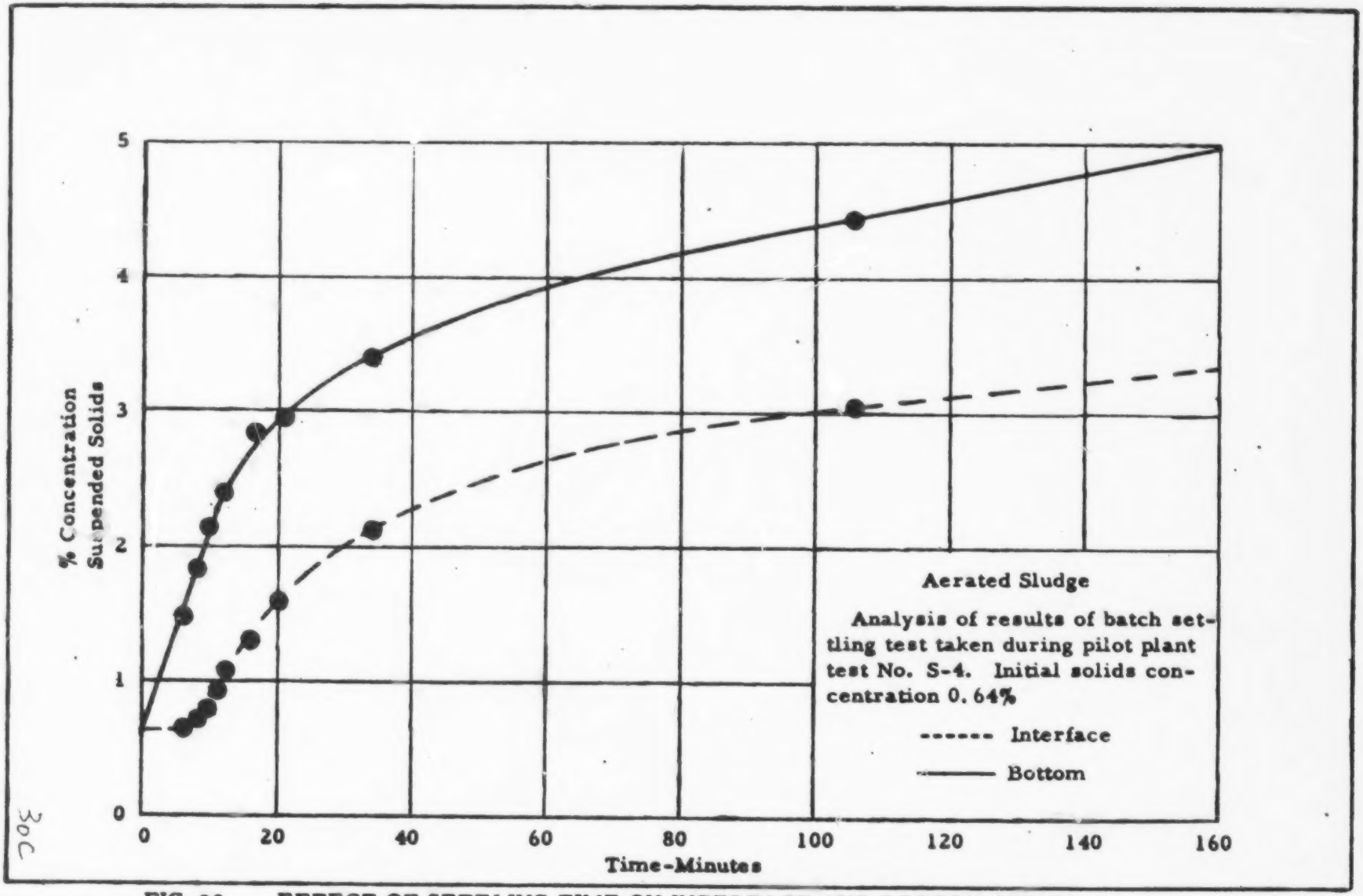

FIG. 28 EFFECT OF SETTLING TIME ON INTERFACE AND BOTTOM SOLIDS CONCENTRATION FOR BATCH TEST TAKEN DURING PILOT PLANT TEST No. S-4

This test was made when the settling characteristics of the sludge were the best (30 min sludge volume index was 27 gram/liter). In this particular batch test it was noted that the sludge appeared quite stable and inert even after three hours of settling. An analysis of the settling data indicates that the ultimate bottom solids concentration (this will be referred to as C_u in the remainder of this report) might be 5.5 or 6.0%. It was not possible to predict the shape or the maximum point in the batch flux curve at low concentrations from this data. This was due to the fact that at concentrations lower than about 0.5% the suspension did not flocculate well and the interface was not well defined. The solids concentration gradient in the pilot plant for this test is shown in Figure 29. This shows very little solids loss in the overflow. If the loading conditions for this pilot plant test are applied to develop the total flux curve as shown in Figure 27 it would appear that at a concentration index (referred to as CI in the remainder of this report) of 6.3% some solids overflow would occur since the value of CI is greater than C_u. In this particular case it might well be that steady state conditions had not been reached regardless of a fairly good solids balance. In general, as was indicated earlier the settleability of the sludge became poorer in the later tests. The maximum batch flux could not be predicted from any of the settling tests and (C_u) varied from 6.0% in the early tests to 4.0% in the later tests.

c. Results of Pilot Plant Tests

The results of the 11 pilot plant tests on aerated supernatant sludge that had a reasonable solids balance are shown in Table 4. Because of the change in solids concentration and sludge volume index (SVI) the data has been grouped into three different sets in accordance with raw feed solids concentration and the 30 min SVI. This is indicated in Figures 30 and 31 which show the effect of solids applied rate on sludge depth and solids

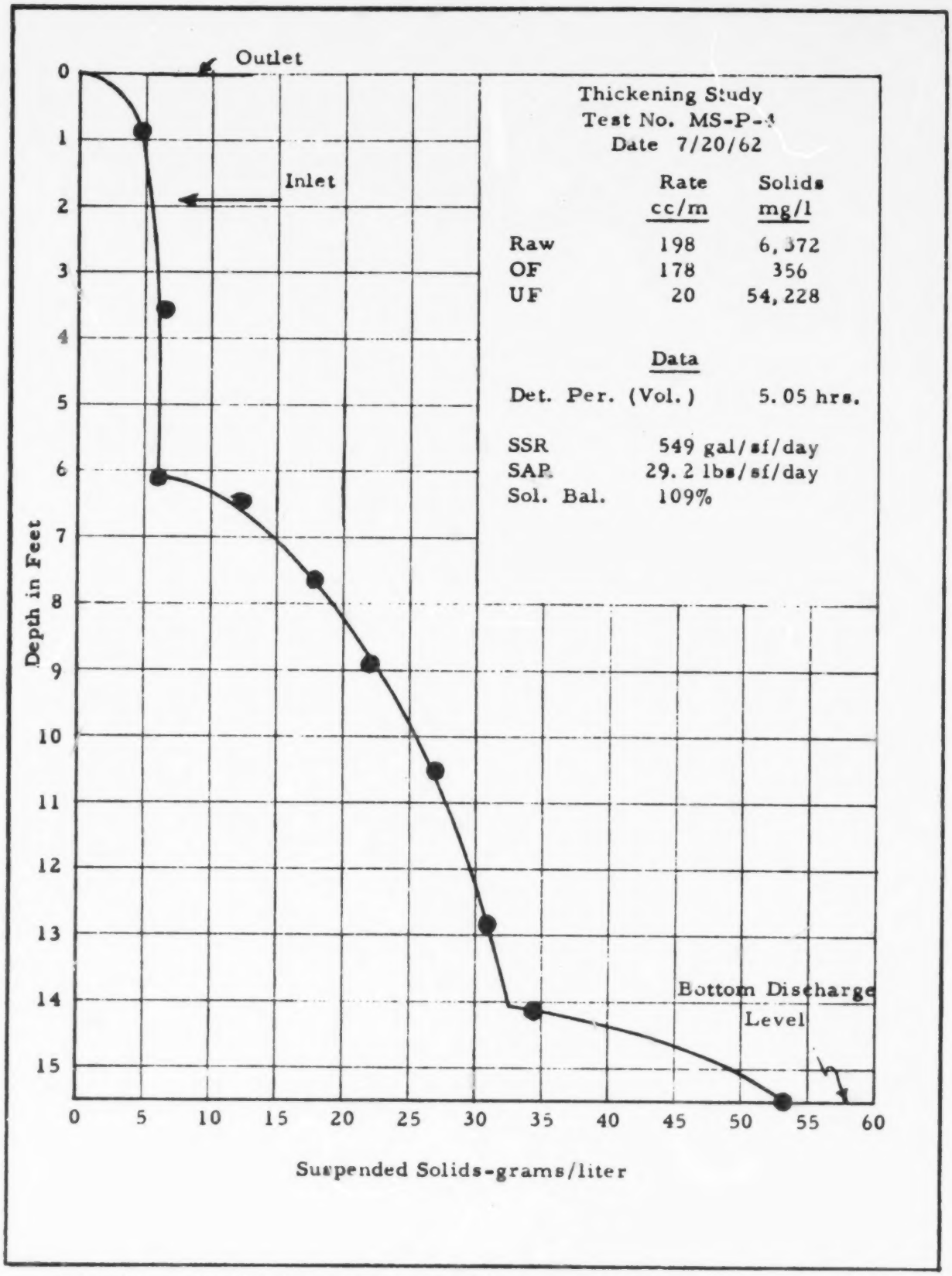

FIG. 29 SUSPENDED SOLIDS GRADIENT IN SLUDGE BLANKET FOR PILOT PLANT TEST No. S-4

TABLE 4

Summary - Pilot Plant Thickening Experiments
Aerated Sludge

Test No.	Flow Ratio	Sol. Conc., mg/l Raw	O. F.	U. F.	Solids Bal. %	Det. Per. Hrs.	SSR *	SAR *	Flow Ratio X SAR	Conc. Index %	Sol. Rem %	Sludge Depth ft.
S-2	10.4	6768	2348	40140	113	2.5	1090	59	610	7.04	68.6	15.5
S-3	9.8	5400	1176	37132	112	1.9	1450	65	644	5.33	80.4	15.5
S-4	9.9	6372	356	54228	109	5.0	549	29	289	6.31	95.0	9.2
S-12	13.9	4984	2596	46360	86	2.5	1110	46	641	6.92	51.7	15.5
S-14	8.6	5016	1628	34880	87	2.5	1113	47	373	6.05	71.5	15.5
S-15	4.8	4880	0	23544	100	5.0	559	23	109	2.34	100.0	10.7
S-16	4.9	10952	180	55216	102	5.0	557	51	249	5.36	87.5	14.9
S-19	6.7	10288	3408	40944	114	5.0	554	48	318	6.88	71.8	15.5
S-20	3.4	7824	308	23104	112	7.0	399	26	88	2.66	97.2	9.2
S-21	4.7	7716	0	31720	114	6.7	415	27	126	3.63	100.0	11.9
S-22	5.2	7528	56	33616	114	6.7	413	26	135	3.91	100.0	12.4

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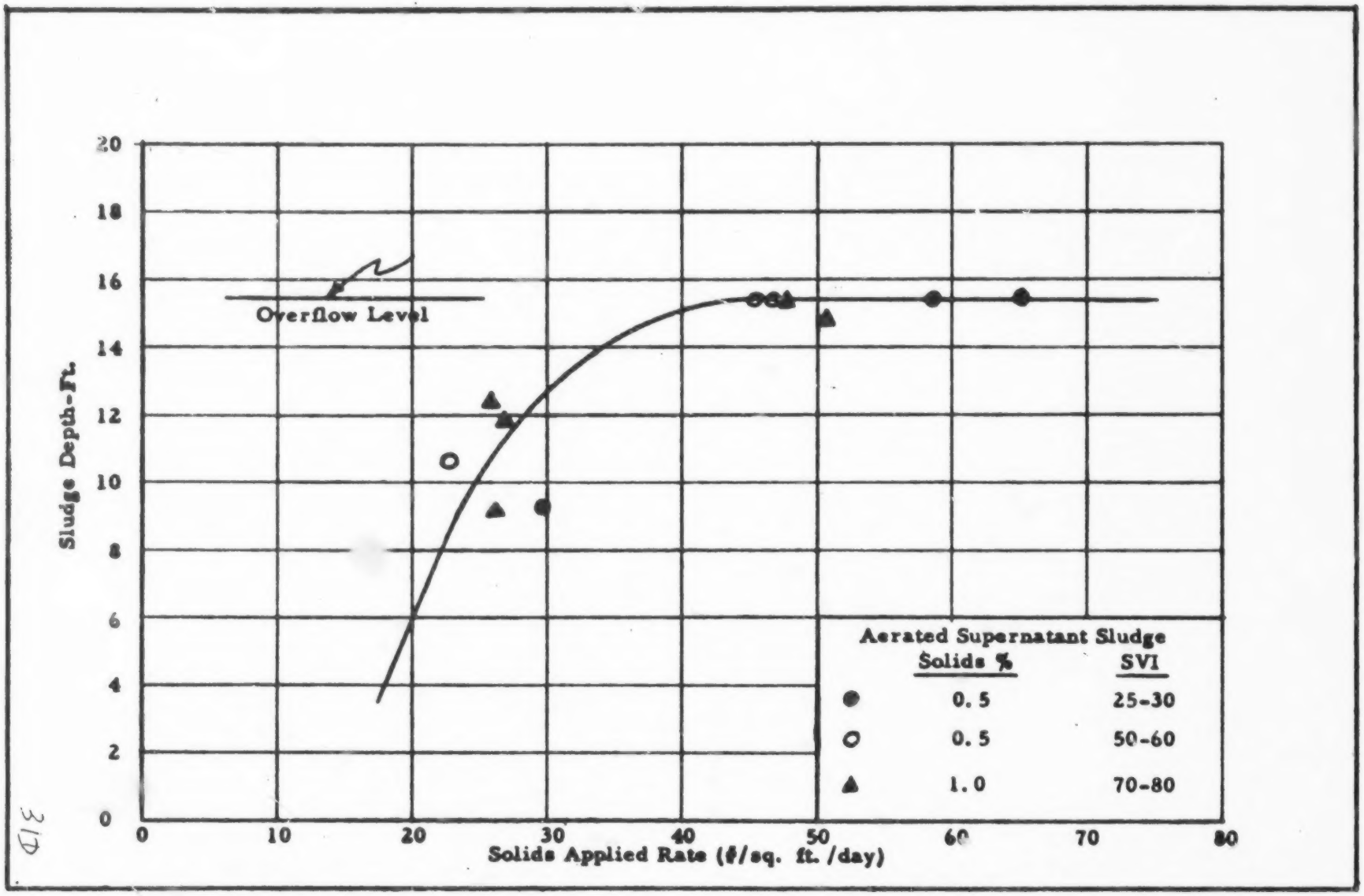

FIG 30 EFFECT OF SOLIDS APPLIED RATE ON SLUDGE DEPTH FOR AERATED SUPERNATANT SLUDGE

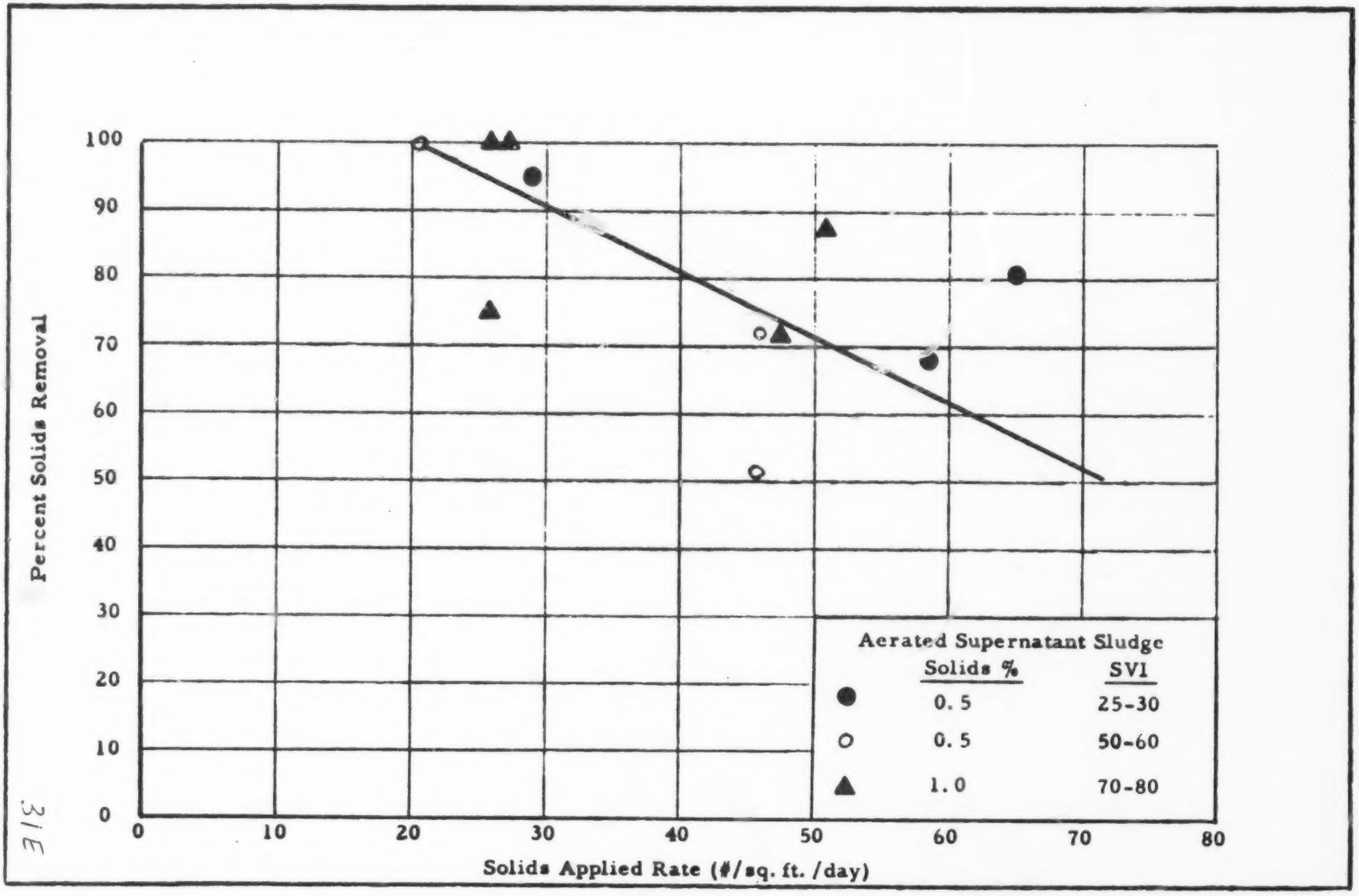

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FIG 31 EFFECT OF SOLIDS APPLIED RATE ON SOLIDS REMOVAL FOR AERATED SUPERNATANT SLUDGE

removal for these tests. Although the data are few and somewhat scattered, these results indicate a limiting solids applied load of 30 to 40 lb/sq ft/day. The effect of concentration index on sludge depth and solids removal is shown in Figures 32 and 33 and indicate that the limiting concentration index to avoid solids loss in the overflow to be 40 to 50 grams/liter (4.0 to 5.0%). Although the limiting solids applied load could not be predicted from the batch tests, the predicted value of (C_u) of 4.0 to 6.0% compare quite well with the results of pilot plant test results.

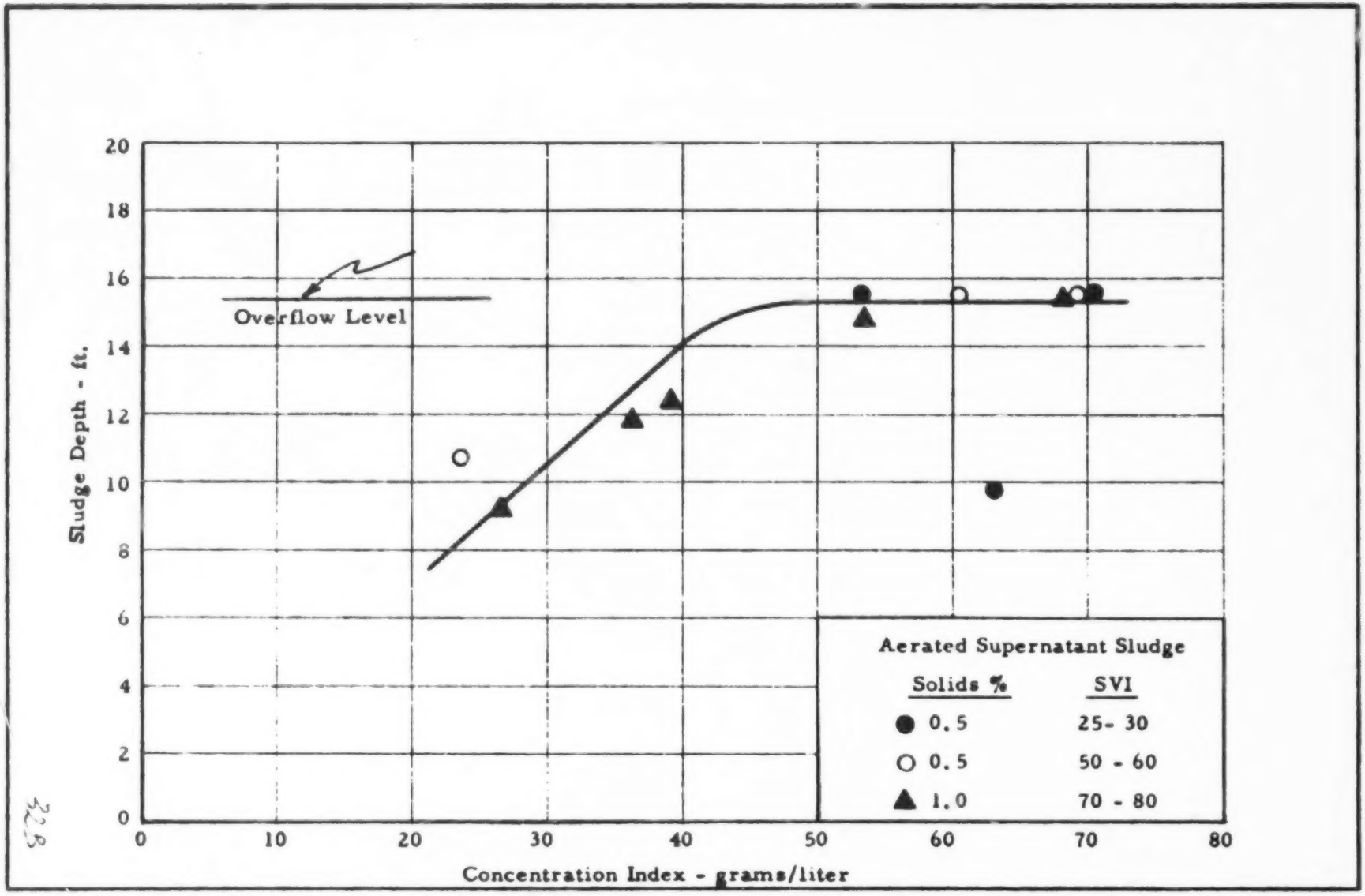

Fig. 32 EFFECT OF CONCENTRATION INDEX ON SLUDGE DEPTH FOR AERATED SUPERNATANT SLUDGE

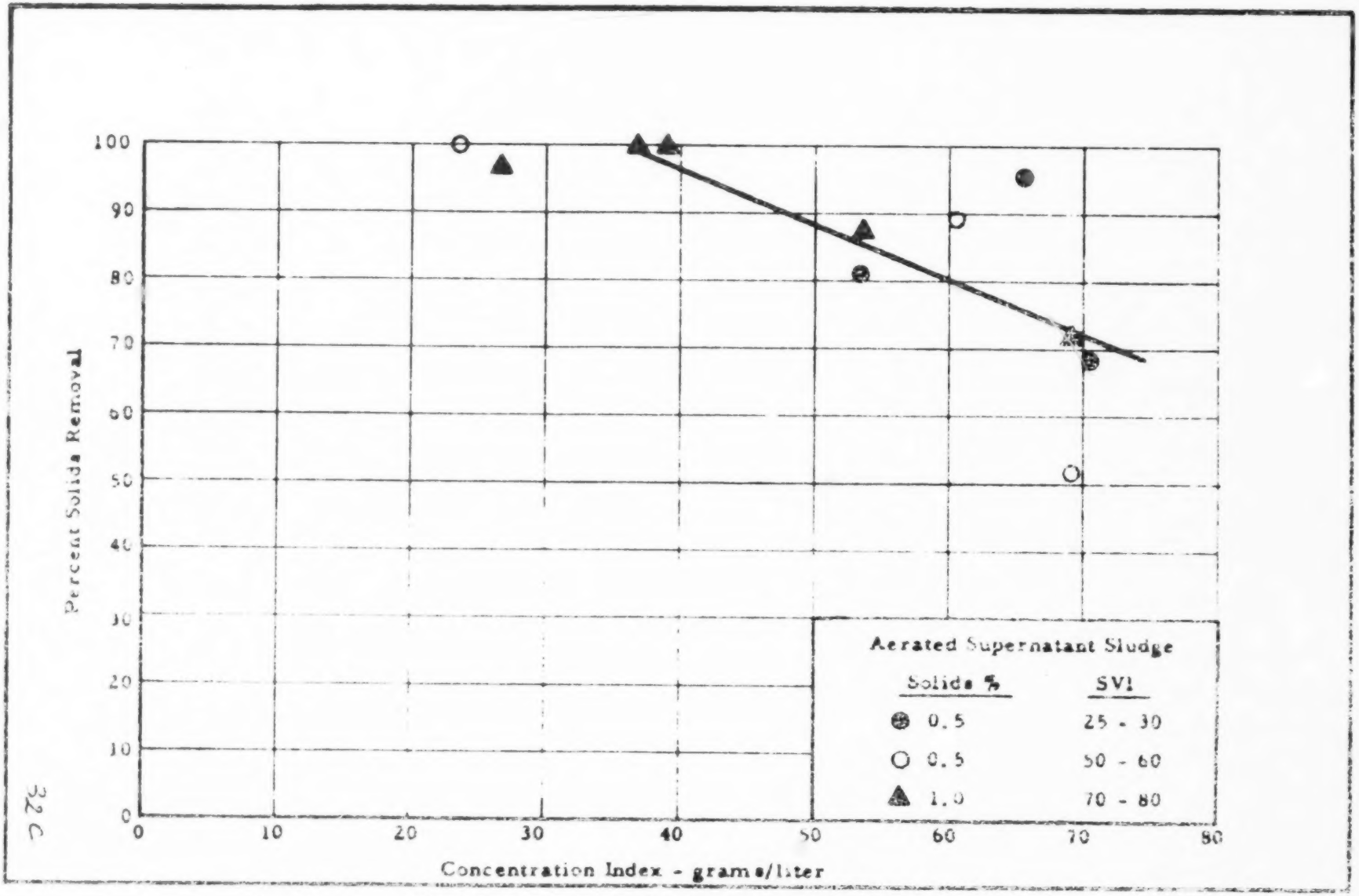

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Fig. 33 EFFECT OF CONCENTRATION INDEX ON SOLIDS REMOVAL FOR AERATED SUPERNATANT SLUDGE

G. INVESTIGATIONS ON PRIMARY SEWAGE SLUDGE

1. General

While the pilot plant was still at the Minneapolis-Saint Paul Sanitary District sewage plant a series of thickening tests were conducted using sludge from the primary sedimentation tanks. The primary sludge is pumped periodically from the sedimentation tanks to the concentration or holding tanks and was quite concentrated (5.0 to 7.0%). It was felt that the pilot plant was too small to get any meaningful results using such a heavy sludge and it was decided to conduct thickening tests on screened primary sludge diluted to approximately 1.0 to 2.0% solids with primary tank effluent. Since it was not possible to obtain a continuous screened and diluted sludge, the sludge sample to be fed to the pilot plant was screened and diluted on a batch basis. This was done by taking a sample of heavy primary sludge each morning (usually 32 gallons). This was diluted with primary effluent to approximately 1.0 to 2.0% solids and screened first through a 1/4 inch screen and then through a 1/8 inch screen. Enough sample was prepared in this way each morning to supply the pilot plant for a 24 hour period. The diluted sample was continuously mixed to insure that a uniform concentration was fed to the pilot plant. It should be recognized however that because of this arrangement, part of the sample was mixed and stored at room temperature for a period of 24 hours before being pumped to the thickening unit.

2. Characteristics of Screened Diluted Primary Sludge

The screened and diluted primary sludge used in these batch and pilot plant investigations was grey to black in color and had a somewhat septic odor. Observation of the material in the pilot plant and batch settling tests indicated a wide variation in the size, shape and nature of the solids. (From heavy inert grit, seeds and coffee grounds to light

flocculent material.) The sludge contained a large amount of fibrous material that appeared to be paper or cellulose fibers. The supernatant in the batch settling tests contained colloidal and dissolved solids (2000 to 3000 mg/liter) that did not settle. The specific gravity of the dry solids measured during these tests ranged from 1.5 to 2.0 and averaged 1.7. The settling characteristics of the sludge as measured by the batch tests varied to a certain extent during these investigations but not in a progressive fashion as in the case of aerated supernatant sludge.

3. Experimental Results on Primary Sludge

a. General

The same general experimental procedures were used in these tests as for the previous tests except as noted above. Because of the fibrous nature of the sludge it was very difficult to obtain steady state conditions in the pilot unit as measured by the solids balance. In many cases test failures were cased by blockages of the underflow line. In other cases when no mechanical difficulties or line blockages occurred, a solids balance was not achieved because of liquid pockets and channeling effects caused by the internal shear forces in the heavy sludge in the bottom of the pilot unit. From a series of over fifty tests only 6 were considered to have achieved steady state conditions. With this low percentage of success experience, the test series was discontinued because it was felt that the pilot unit was too small to get meaningful results, especially at high underflow solids concentrations.

b. Batch Test Results

The batch test results taken during all of the tests of this series even when the pilot plant test failed give a fairly good picture of the settling characteristics of diluted primary sludge. An analysis of the results of the batch test taken during pilot plant test P-1 (which shows a

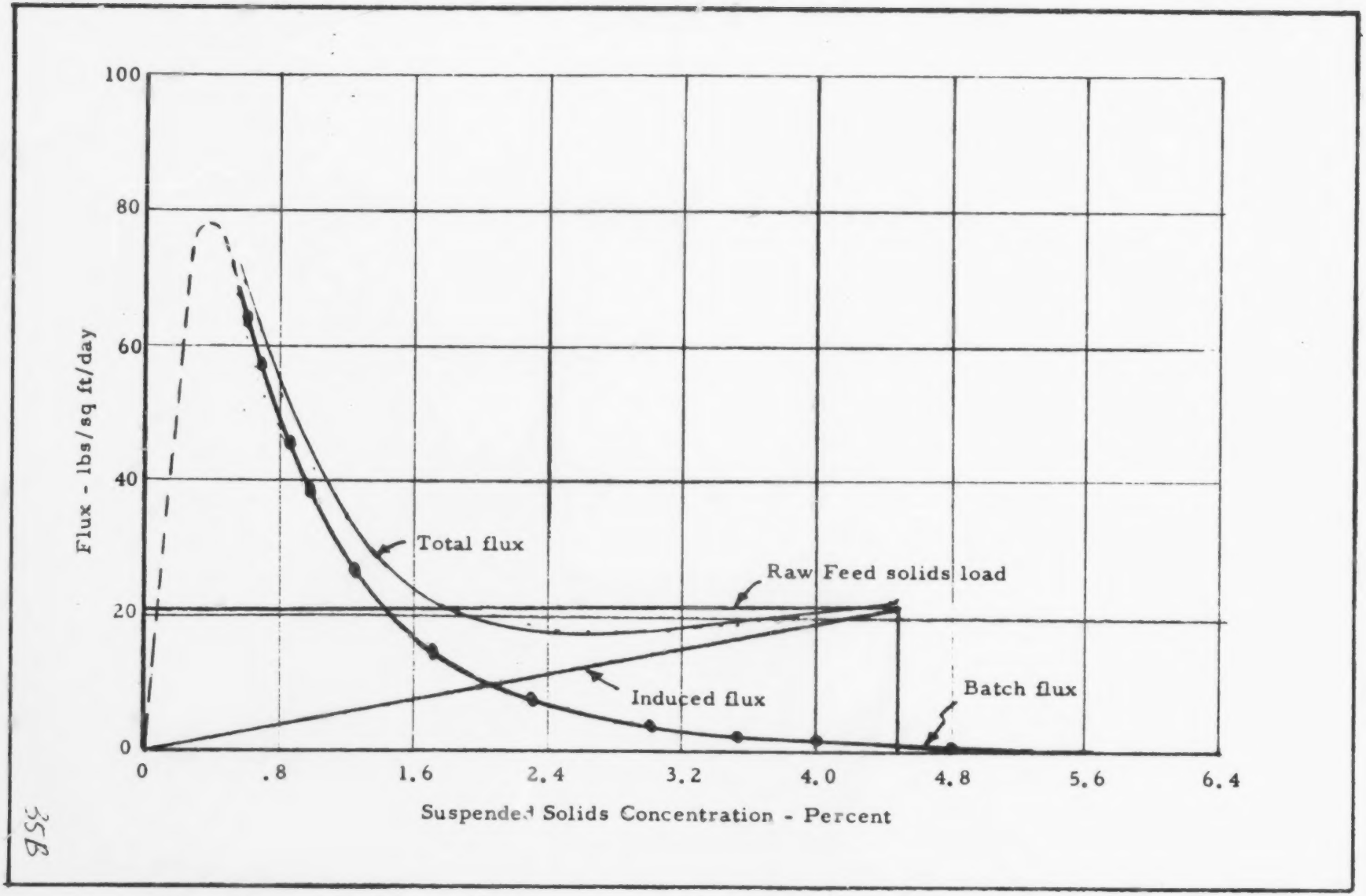
fairly good solids balance) will be used as a typical example. The batch flux curve shown in Figure 34 indicates that an estimate of the maximum flux cannot be predicted from the results of a batch settling test because at low solids concentrations (below 0.6% solids) the interface is diffuse and not well defined. As a matter of conjecture it might be that this critical concentration approximates the limiting flux (or maximum solids applied load in a continuous flow thickener) because at concentrations below this value, the solids do not tend to flocculate very rapidly and could be swept up and out with the overflow. The bottom and interface solids concentrations shown in Figure 35 for this test indicates (C_u) of about 6.0%.

The solids concentration gradient for pilot plant test P-1 are shown in Figure 36 and the loading conditions for this test have been applied to develop the total flux or loading curve as shown in Figure 34. An analysis of this data as described earlier indicates that under these loading conditions (SAR = 21 lb/sq ft/day CI = 56500 mg/l or 5.65%) the batch test results would predict no solids overflow. It is also noted that the solids concentrations in the zones that occur in the pilot plant can be explained on the basis of the relationship between the total flux curve and raw feed solids loading which are shown in Figure 34.

In general, a review of all of the results of batch tests conducted on primary sludge during this series indicate a probable maximum batch flux of 60 to 80 lb/sq ft/day with a limiting C_u of 6.0 to 8.0%.

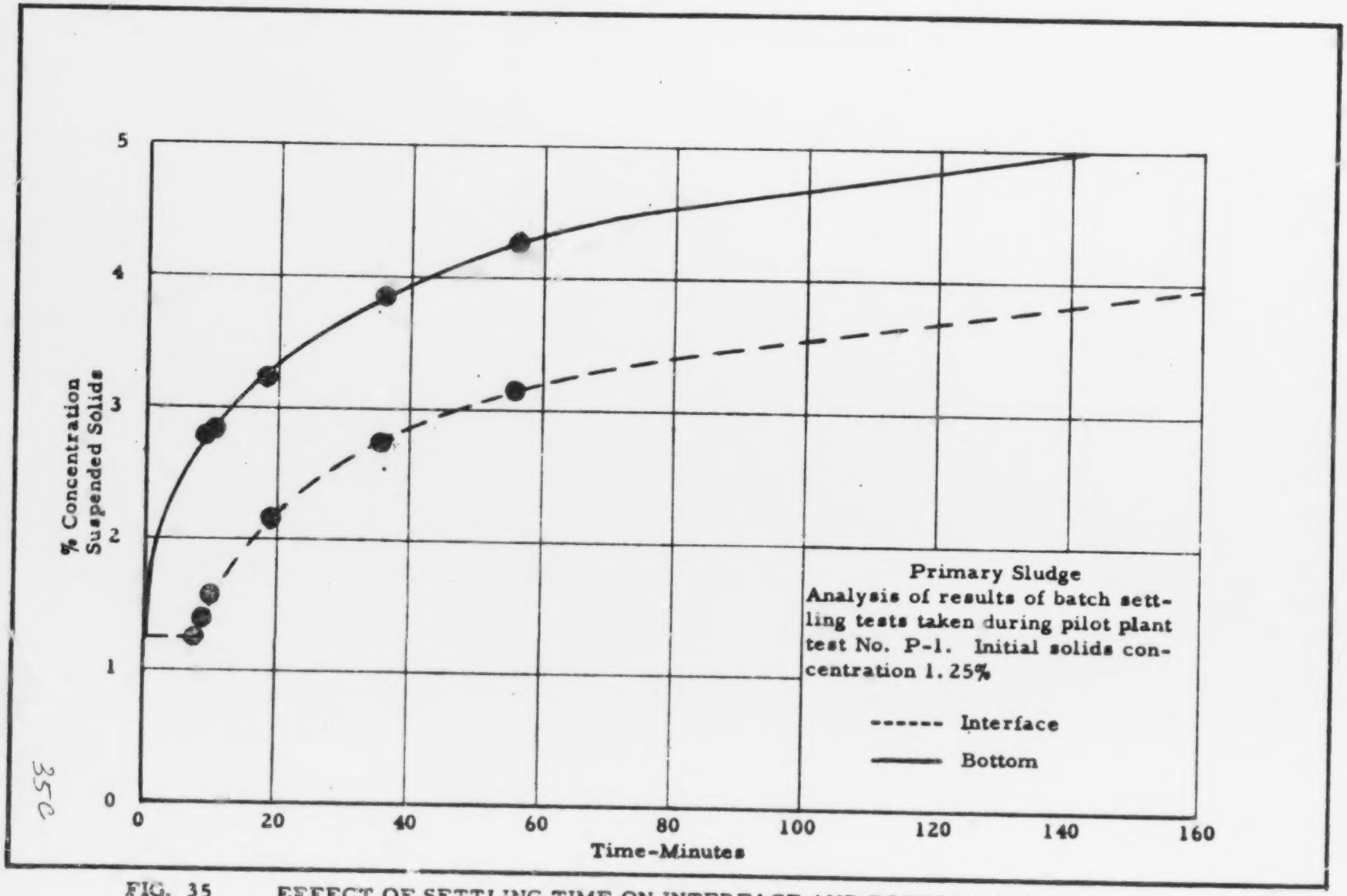
c. Pilot Plant Results

The results of the 6 pilot plant tests on primary sludge that had a reasonable solids balance are shown in Table 5. With such a limited amount of data it is realized that only some very general trends can be indicated. The effect of the solids applied rate on sludge depth and solids removal is shown in Figures 37 and 38. The data have been divided into



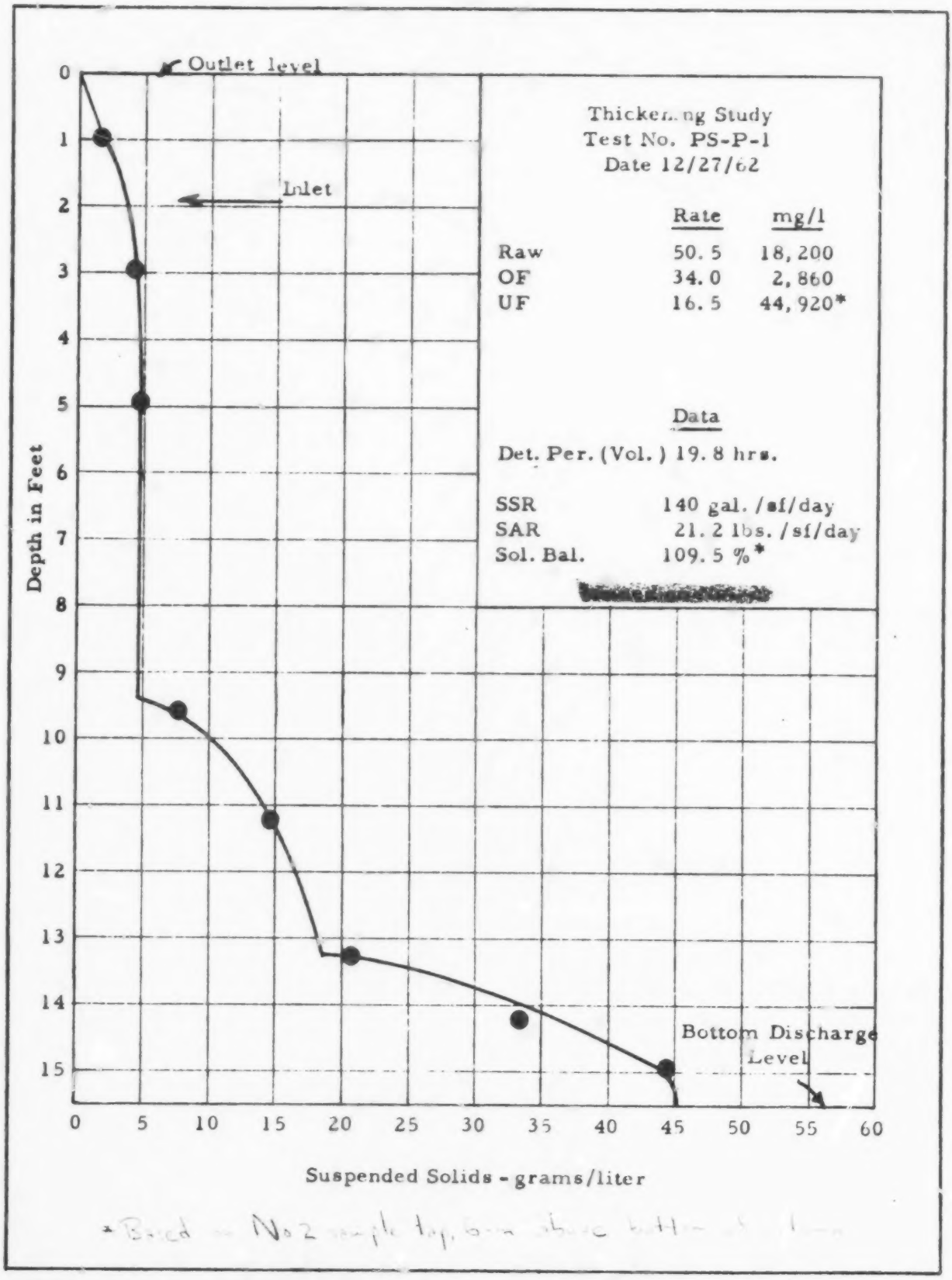
35B

FIG. 34 FLUX CURVES FOR PILOT PLANT TEST NO. P-1



350

FIG. 35 EFFECT OF SETTLING TIME ON INTERFACE AND BOTTOM SOLIDS CONCENTRATION FOR BATCH TEST TAKEN DURING PILOT PLANT TEST NO. P-1


Outlet level
Inlet
Thickening Study
Test No. PS-P-1
Date 12/27/62
Rate mg/l
Raw 50.5 18,200
OF 34.0 2,860
UF 16.5 44,920*
Data
Det. Per. (Vol.) 19.8 hrs.
SSR 140 gal./sf/day
SAR 21.2 lbs./sf/day
Sol. Bal. 109.5 %*
Bottom Discharge Level
Depth in Feet
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
0 5 10 15 20 25 30 35 40 45 50 55 60
Suspended Solids - grams/liter

*Based on No 2 sample top, bottom above bottom of [illegible]

FIG. 36 SUSPENDED SOLIDS GRADIENT IN SLUDGE BLANKET FOR PILOT PLANT TEST NO. P-1

35 D

TABLE 5

SUMMARY -- PILOT PLANT THICKENING EXPERIMENTS
PRIMARY SLUDGE

Test No.	Flow Ratio	Susp. Sol. mg/l			Solids Bal. %	Det. Period Hr.	SSR	SAR	Flow Ratio X SAR	Conc. Index mg/l	Sol. Rem. %	Sludge Depth ft.
		Raw	O.F.	U.F.								
P-1	3.1	18200	8860	44920	109.5	19.8	140	21.2	65.7	56500	84.3	6.0
P-2	2.8	25464	4480	83808	100.5	10.10	273	58.3	163	71000	82.5	13.5
P-3	4.0	24940	13468	57720	101.3	10.5	263	54.8	219	99750	46.0	14.5
P-4	5.2	23244	13748	77968	89	10.2	271	52.6	274	120800	40.9	14.5
P-5	6.8	12484	2272	69256	112.0	3.67	755	78.5	534	84800	80.2	14.5
P-6	8.5	11992	6068	68940	89.8	3.37	823	82.2	699	141000	49.4	14.5
P-7	3.2	13272	2396	36324	103	6.72	413	45.7	146	42400	82	4.5

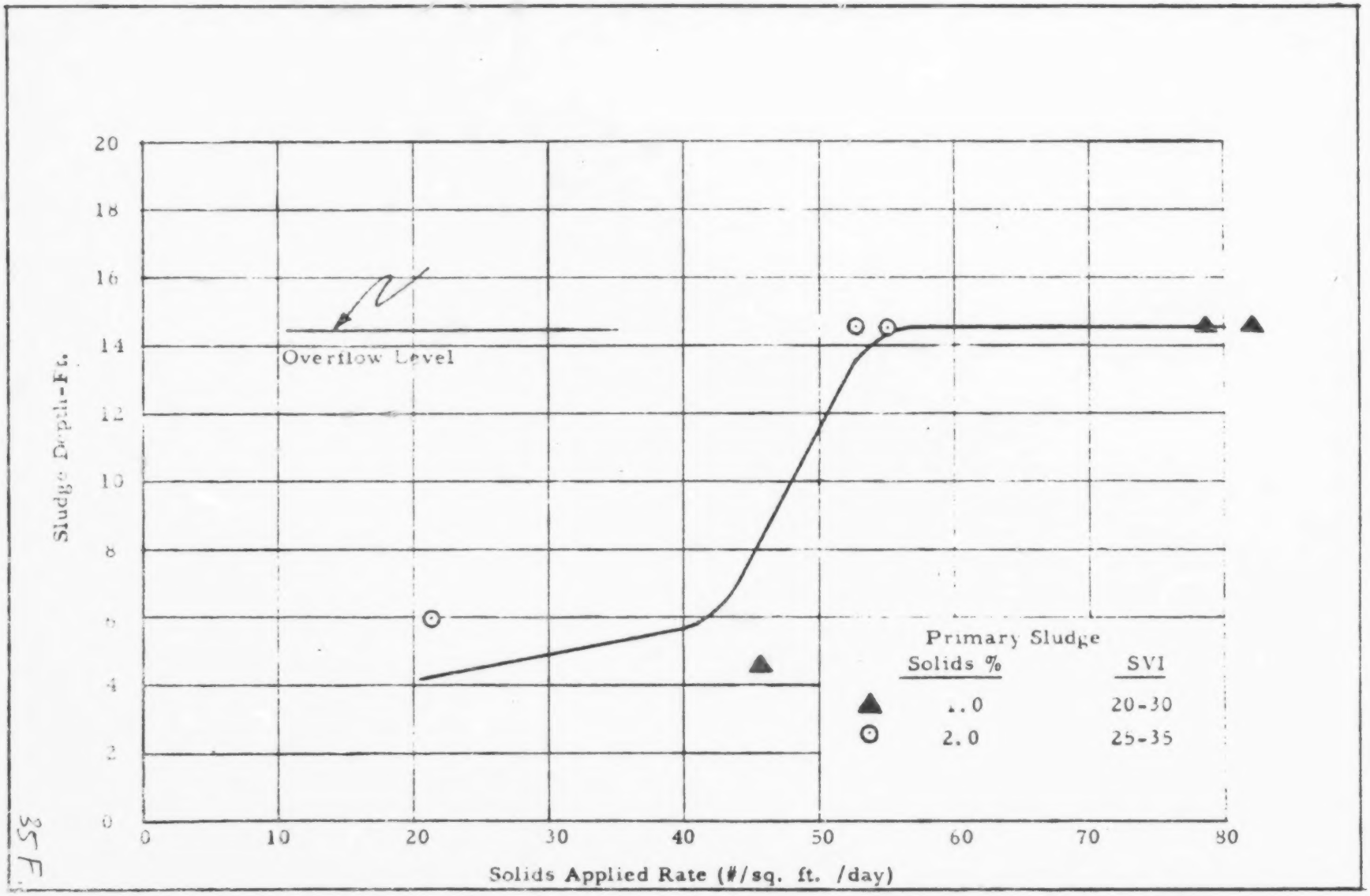


FIG 37 EFFECT OF SOLIDS APPLIED RATE ON SLUDGE DEPTH FOR PRIMARY SLUDGE

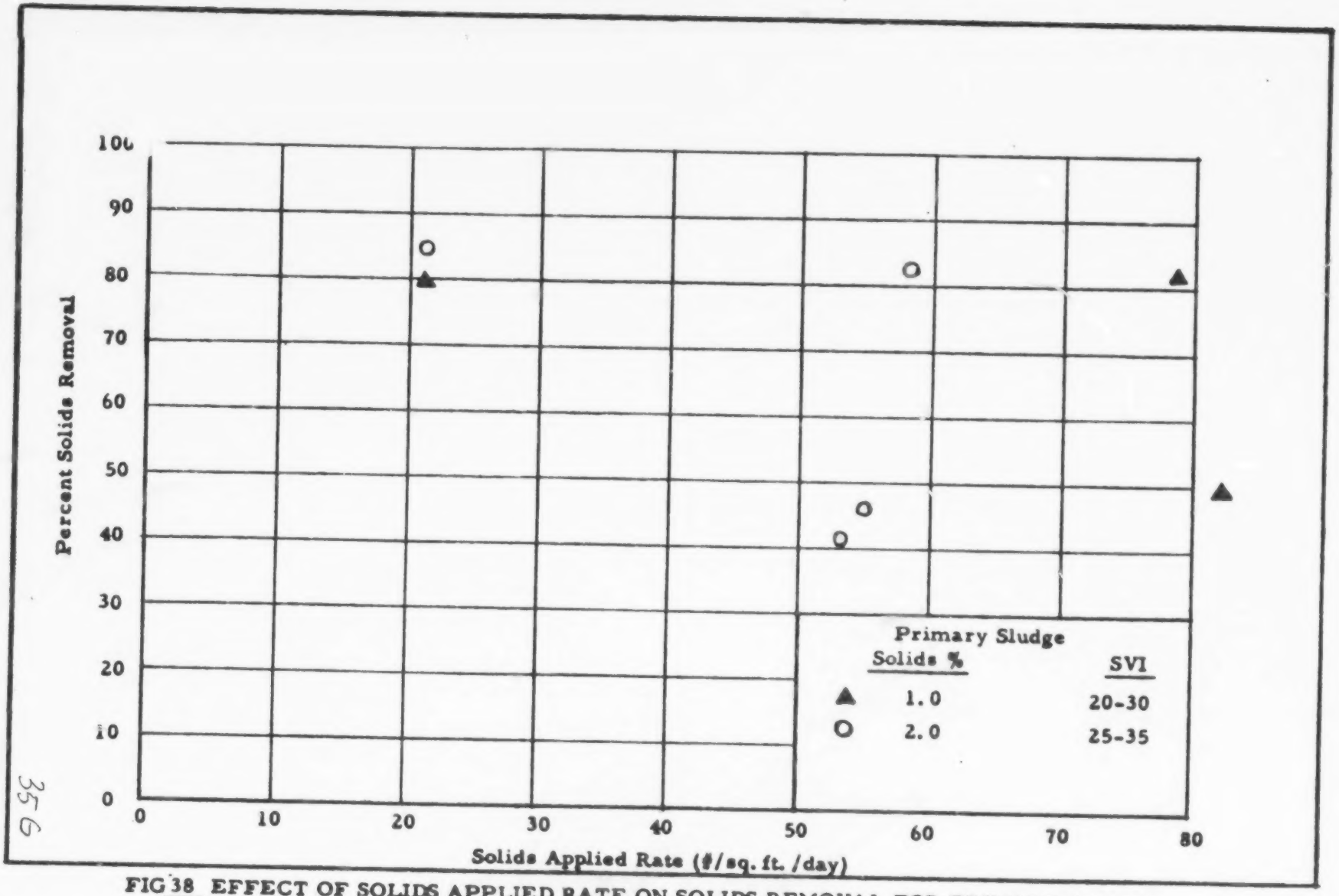


FIG 38 EFFECT OF SOLIDS APPLIED RATE ON SOLIDS REMOVAL FOR PRIMARY SLUDGE

two groups in accordance with the raw feed solids concentration. From these results it appears that within the range tested the raw feed solids concentration have no measurable effect on the results and that the maximum solids applied load for minimum solids loss is about 50 to 55 lb/sq ft/day. The data on solids removal efficiency are so erratic as to preclude any conclusions. The effect of the concentration index on sludge depth and solids removal is shown in Figures 39 and 40. These results indicate a limiting CI of 6.0 to 7.0%. Considering the limited number of pilot plant data these limiting loading conditions for primary sludge thickening compare quite favorably with those predicted from the batch tests.

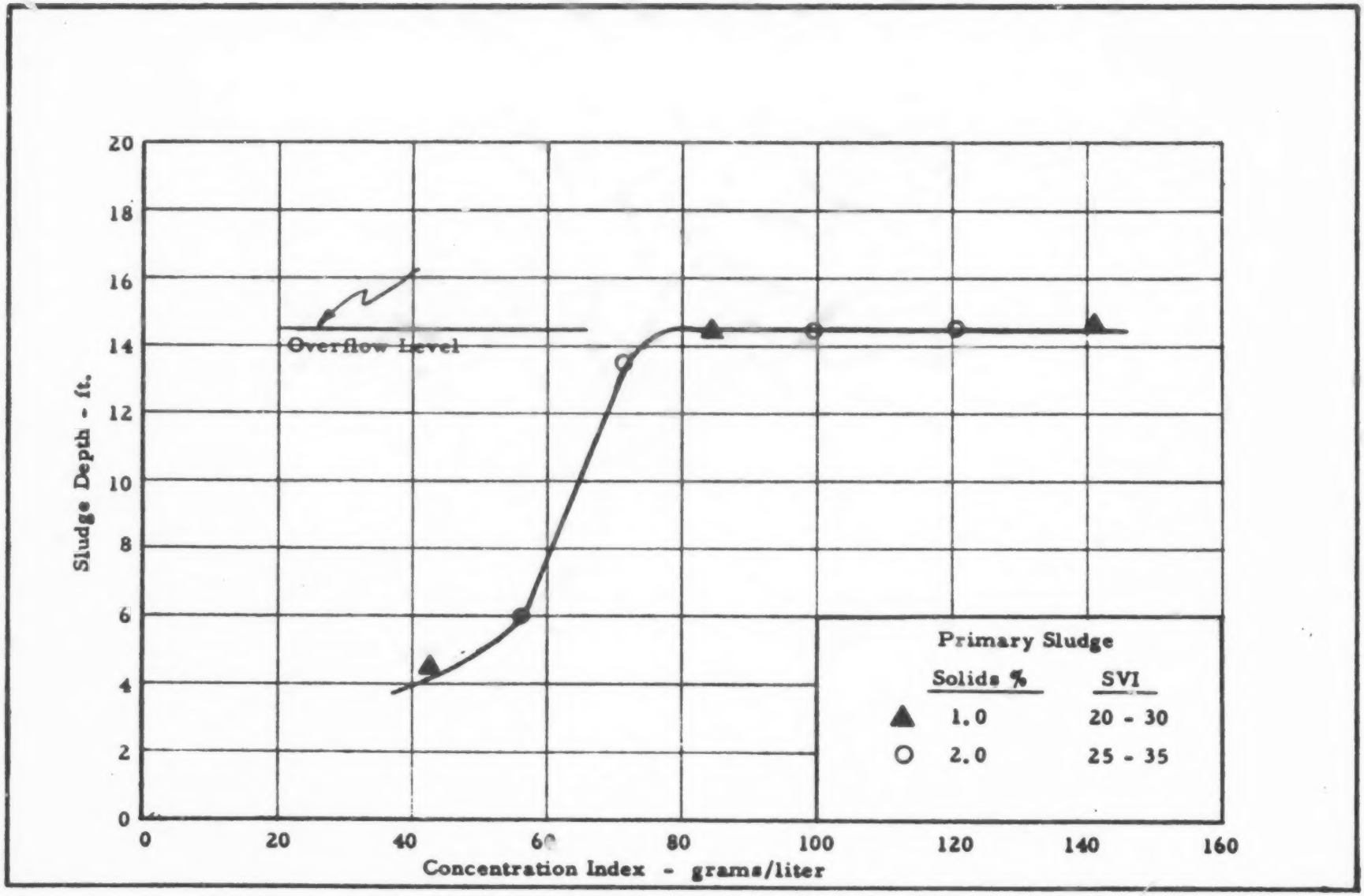


Fig. 39 EFFECT OF CONCENTRATION INDEX ON SLUDGE DEPTH FOR PRIMARY SLUDGE

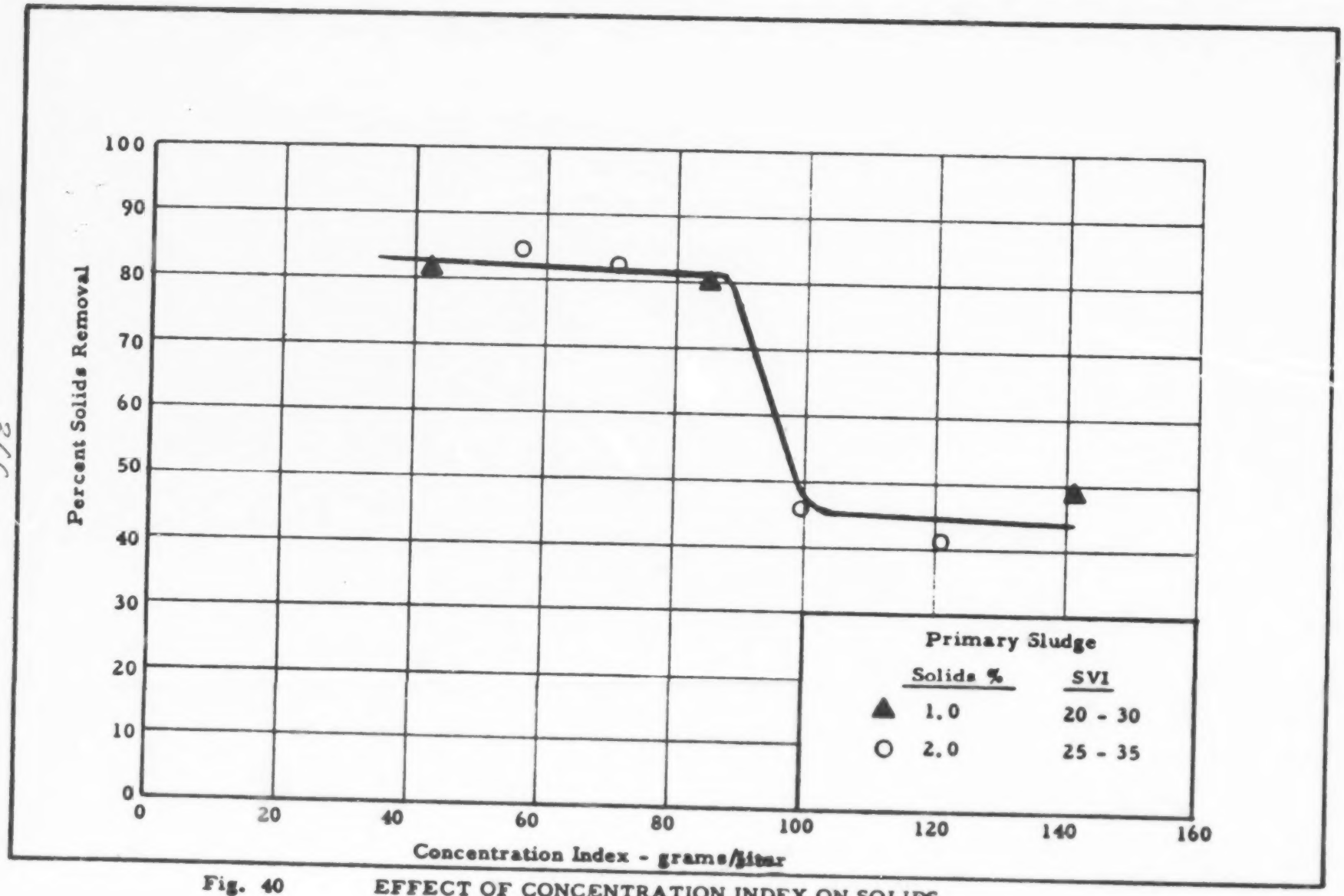


Fig. 40 EFFECT OF CONCENTRATION INDEX ON SOLIDS REMOVAL FOR PRIMARY SLUDGE

H. INVESTIGATIONS ON ANAEROBIC SLUDGE

1. General

A series of thickening investigations were conducted on anaerobic sludge at the anaerobic treatment plant operated by the Wilson & Co. at Albert Lea, Minnesota. The treatment plant uses the anaerobic contact process applied to packing plant wastes from Wilson & Co. The batch and continuous flow pilot plant thickening tests were conducted on the degasified sludge which was being fed to the large scale sludge separators. The raw feed to the pilot unit was pumped directly from a sludge sampling well and was continuously screened through a 1/8 inch screen to remove large solids and straw.

2. Characteristics of Anaerobic Sludge

The degasified anaerobic sludge used in these studies was black in color and could be described characteristically as a suspension of anaerobic biologically active floc. The sludge remained quite uniform during the period of testing. The solids concentration in the feed to the pilot plant ranged from 5400 to 7000 mg/l but for the most part remained at about 6000 mg/liter. The settling characteristics of the sludge as measured by the batch settling tests were also fairly constant. The sludge was so extremely active that after settling for a period of 40 to 50 min the gas formation would cause flotation of the solids. The supernatant was quite clear except when gas formation would cause sludge particles to rise to the surface. The specific gravity of the dry solids from a number of tests ranged from 1.3 to 1.6 and averaged about 1.4.

3. Experimental Results on Anaerobic Sludge

a. General

The same general procedures described earlier were used in the tests on anaerobic sludge with the exception that because of the short detention periods the pilot plant tests reached equilibrium in a much shorter time and the length of each pilot plant run was shortened to about 6 to 8 hrs instead of 24 hours.

b. Batch Test Results

Batch tests were conducted concurrently with each of the 14 pilot plant tests on anaerobic sludge. Two samples were run in each test, one at the same concentration as the raw feed and one diluted 1 to 1 with clear supernatant. The results of all of the tests were quite similar and indicated that because of the extremely active nature of the sludge the maximum concentration was reached in 40 to 50 min after which flotation caused a reduction in the bottom concentration of solids. An analysis of the batch test results taken during pilot plant test A-7 will be used as a typical example. The batch flux curve and the bottom and interface solids concentrations computed for this test are shown in Figures 41 and 42. The batch flux curve does not show the maximum point in this case because the lowest concentration used in the batch settling tests was about 3000 mg/liter and the interface was still very well defined. Several months after the pilot plant tests were complete tests were made on a series of dilutions with solids concentrations of 500, 1000, 1500, 2000, and 3000 mg/liter. This test indicated the critical point for the formation of a well defined interface was at a solids concentration of about 1500 mg per liter and that the maximum batch flux at this point was about 120 lb/sq ft/day. The batch flux curve shown in Figure 41 has been extrapolated (shown by dotted line) based on the results of this later test. The results in Figure 42 indicate a value for

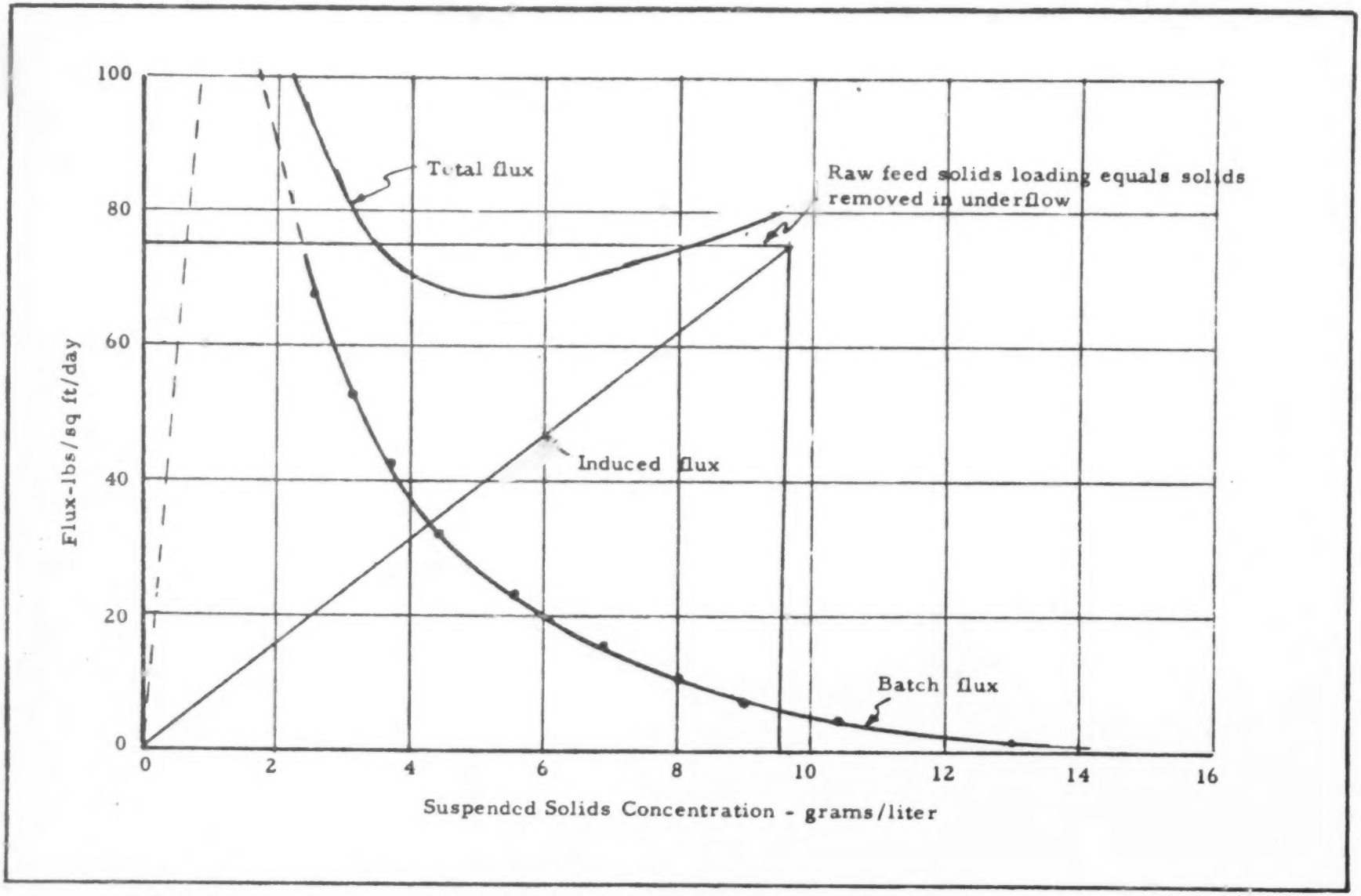


FIG. 41 FLUX CURVE FOR PILOT PLANT TEST NO. A-7

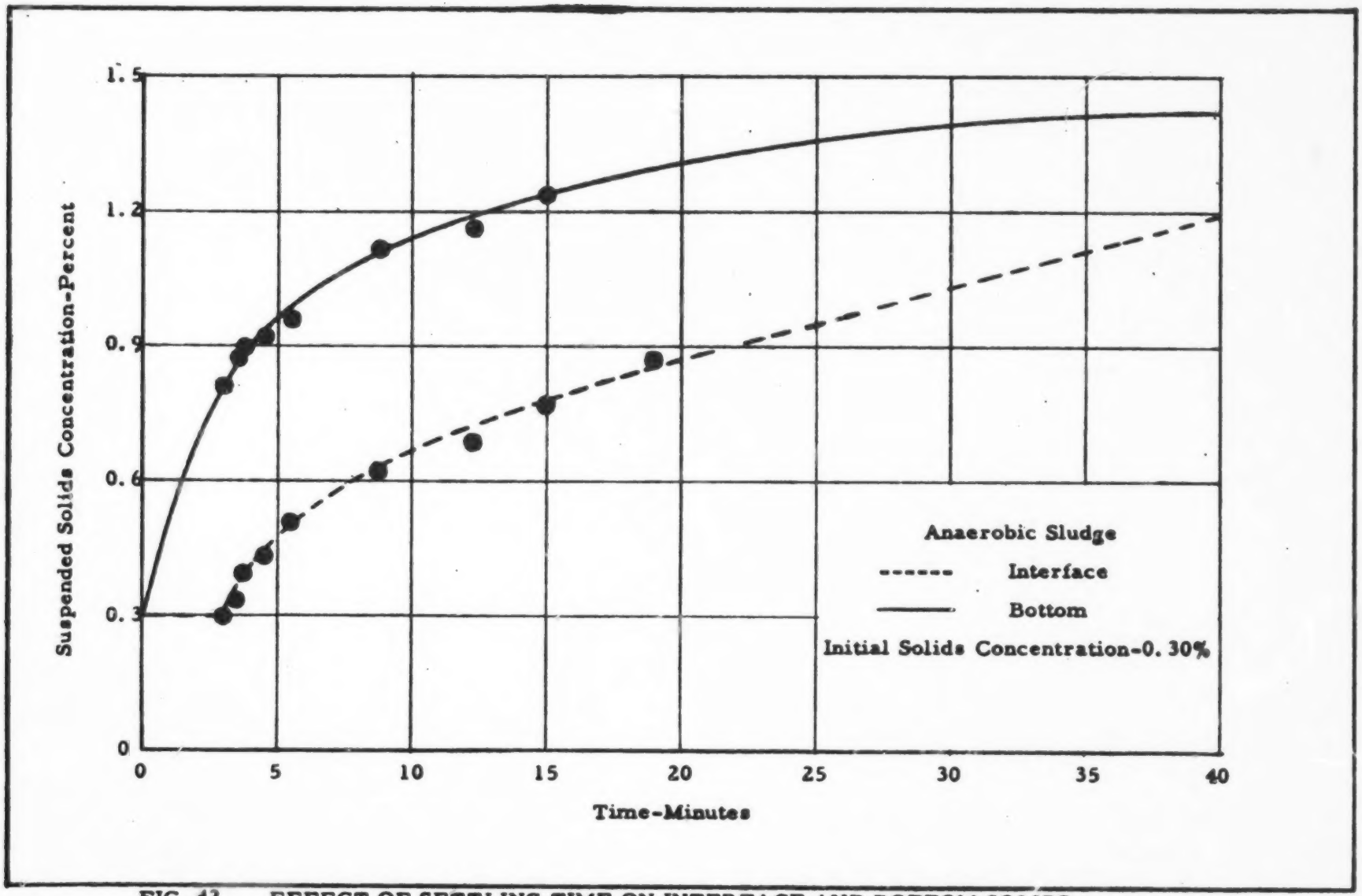


FIG. 42 EFFECT OF SETTLING TIME ON INTERFACE AND BOTTOM SOLIDS CONCENTRATION FOR BATCH TEST TAKEN DURING PILOT PLANT TEST No. A-7

38C

(C_u) of about 1.4%. This is quite typical because the value of (C_u) for the other batch tests that were conducted in this series ranged only from 1.3 to 1.5%.

The solids gradient diagram for pilot plant test A-7 is shown in Figure 43 and the loading conditions for this test are applied to develop the total flux curve as shown in Figure 44. It is evident that no solids loss in the overflow would be predicted for these thickener loading conditions (SAR = 75.6 lb/sq ft/day and C.I. = 1.0%) based on the batch test results.

c. Pilot Plant Results

The results of the pilot plant tests conducted on anaerobic sludge are shown in Table 6. The tests have been divided into two series. In Series 1 the solids applied rate was varied and the concentration index was maintained as nearly constant as possible. In Series 2 the concentration index was varied at almost constant solids load. The results of Series 1 on the effect of solids loading on sludge depth and solids removal are shown in Figures 44 and 45 and the results of Series 2 on the effect of concentration index on sludge depth and solids removal are shown in Figures 46 and 47. These results indicate a limiting solids applied load of about 130 lb/sq ft/day and a maximum concentration index of 12 to 14 grams/liter (1.2 to 1.4%). These results are fairly close to those predicted by the batch tests.

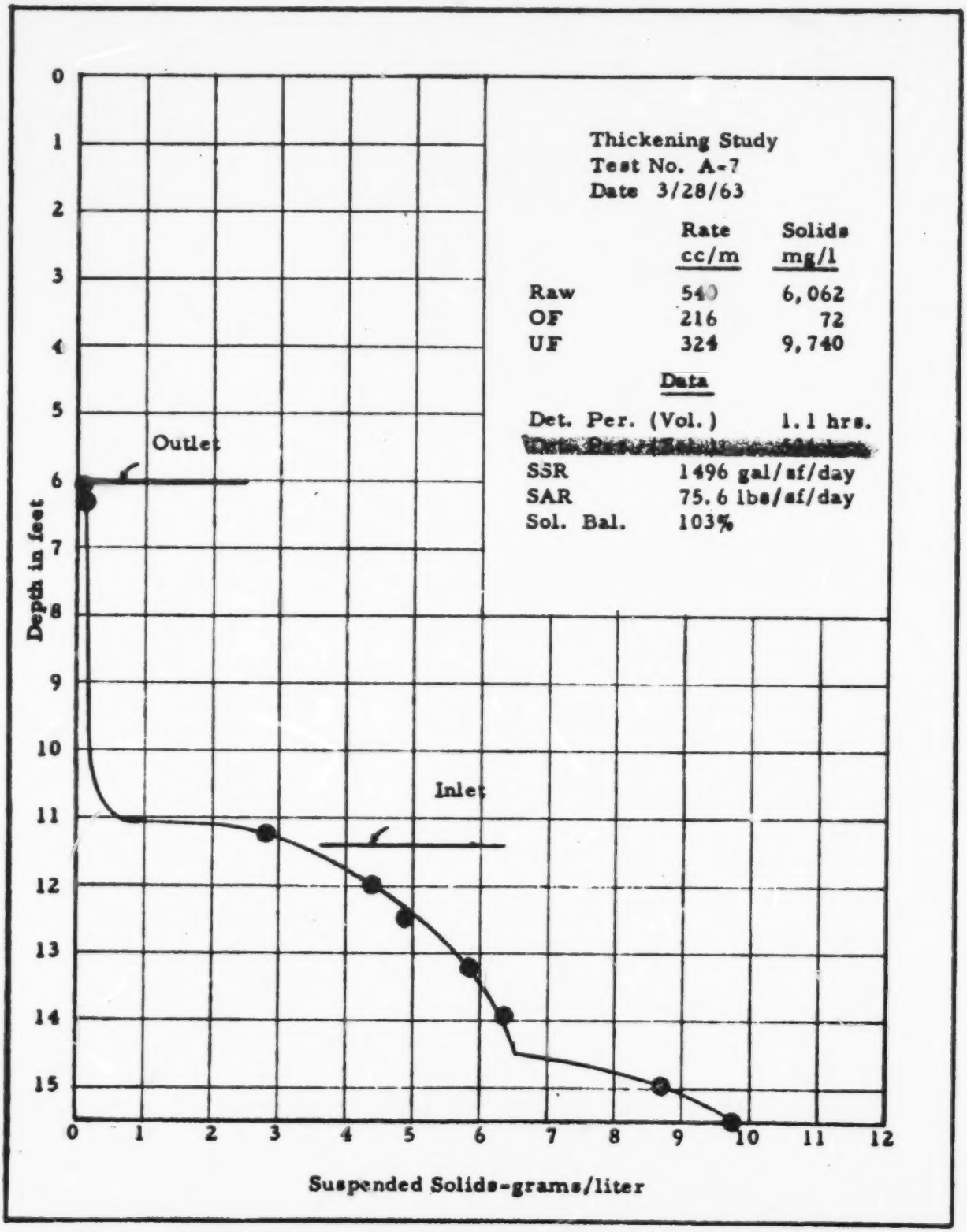


FIG. 43 SUSPENDED SOLIDS GRADIENT IN SLUDGE BLANKET FOR PILOT PLANT TEST NO. A-7

TABLE 6

Summary -- Pilot Plant Thickening Experiments

Anaerobic Sludge

Test No.	Flow Ratio	Susp. mg/l Raw	Sol. mg/l O. F.	Sol. mg/l U.F.	Solids Bal. %	Det. Per. Hrs.	SSR *	SAR *	Flow Ratio X SAR	Conc. Index mg/l	Sol. Rem. %	Sludge Depth ft.
A-1	1.5	5578	288	8976	92	1.7	997	46	70	8367	98.3	0.5
A-2	1.5	5538	200	9072	92	1.1	1512	70	106	8418	98.8	1.2
A-3	1.5	5612	128	8248	102	.8	1992	93	140	8418	99.2	1.0
A-4	1.5	6064	0	8100	112	.7	2493	126	189	9096	100.0	7.0
A-5	1.3	6286	200	7912	105	1.1	1496	78	104	8360	99.2	0.5
A-6	1.5	6290	92	8828	106	1.1	1487	78	116	9372	99.5	0.5
A-7	1.7	6062	72	9740	103	1.1	1496	75	126	10124	99.5	2.0
A-8	2.0	6010	2328	10324	95	1.1	1496	75	150	12020	80.6	8.5
A-9	1.5	5934	268	10560	83	1.1	1496	74	111	8901	98.5	1.3
A-10	1.5	6248	848	8852	101	1.7	1496	78	117	9372	95.5	0.7
A-11	3.0	5382	2748	11928	93	1.3	1994	90	268	16146	55.0	13.5
A-12	1.5	5808	140	8640	100	1.3	1994	97	145	8712	99.2	1.0
A-13	1.5	6178	816	8040	110	1.0	2493	128	192	9267	95.6	13.5
A-14	1.5	7008	148	9988	104	1.3	1994	117	175	10512	99.3	5.6

39-C

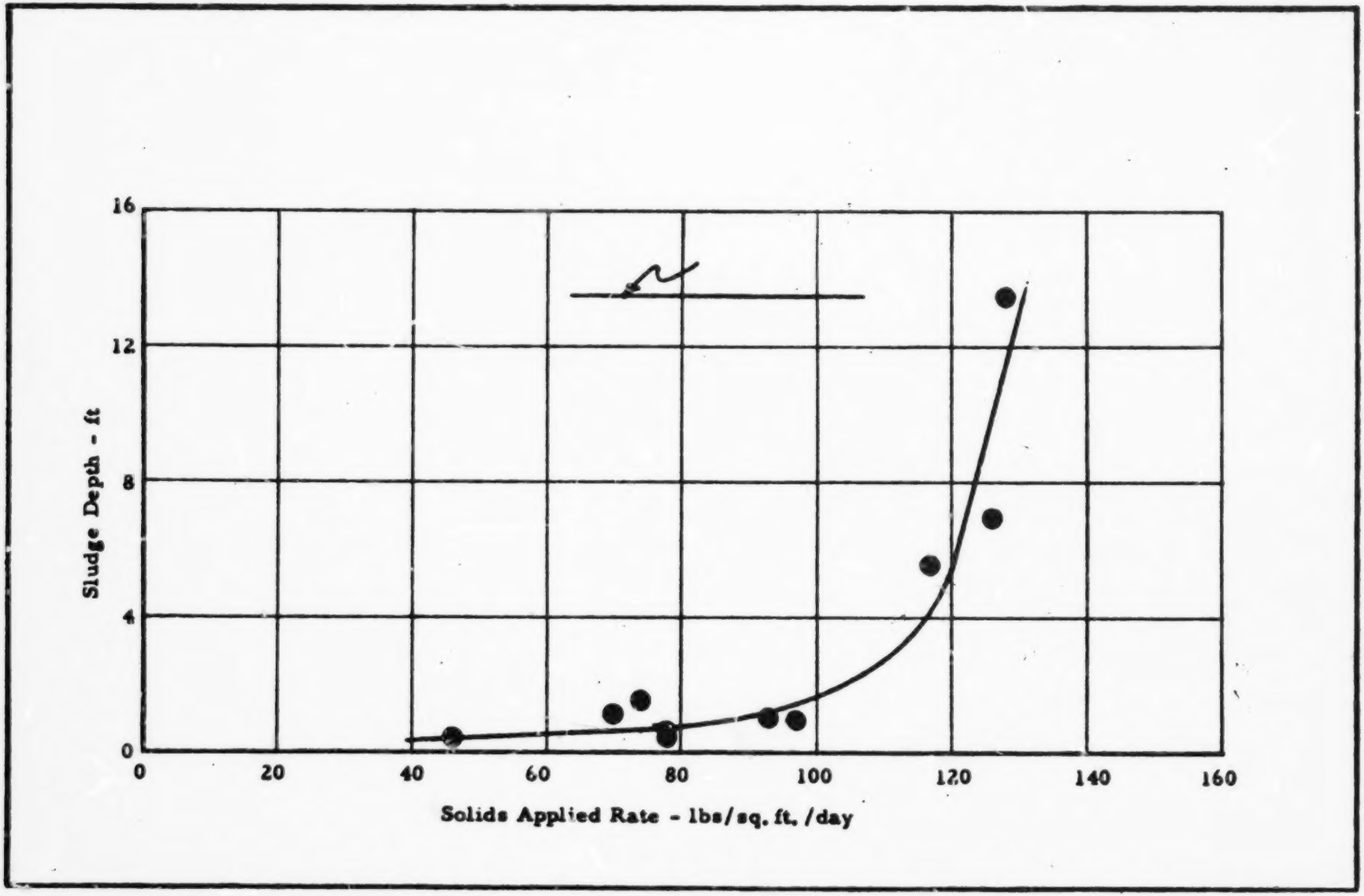


FIG. 44 EFFECT OF SOLIDS APPLIED RATE ON SLUDGE DEPTH FOR ANAEROBIC SLUDGE - SERIES 1

39-D

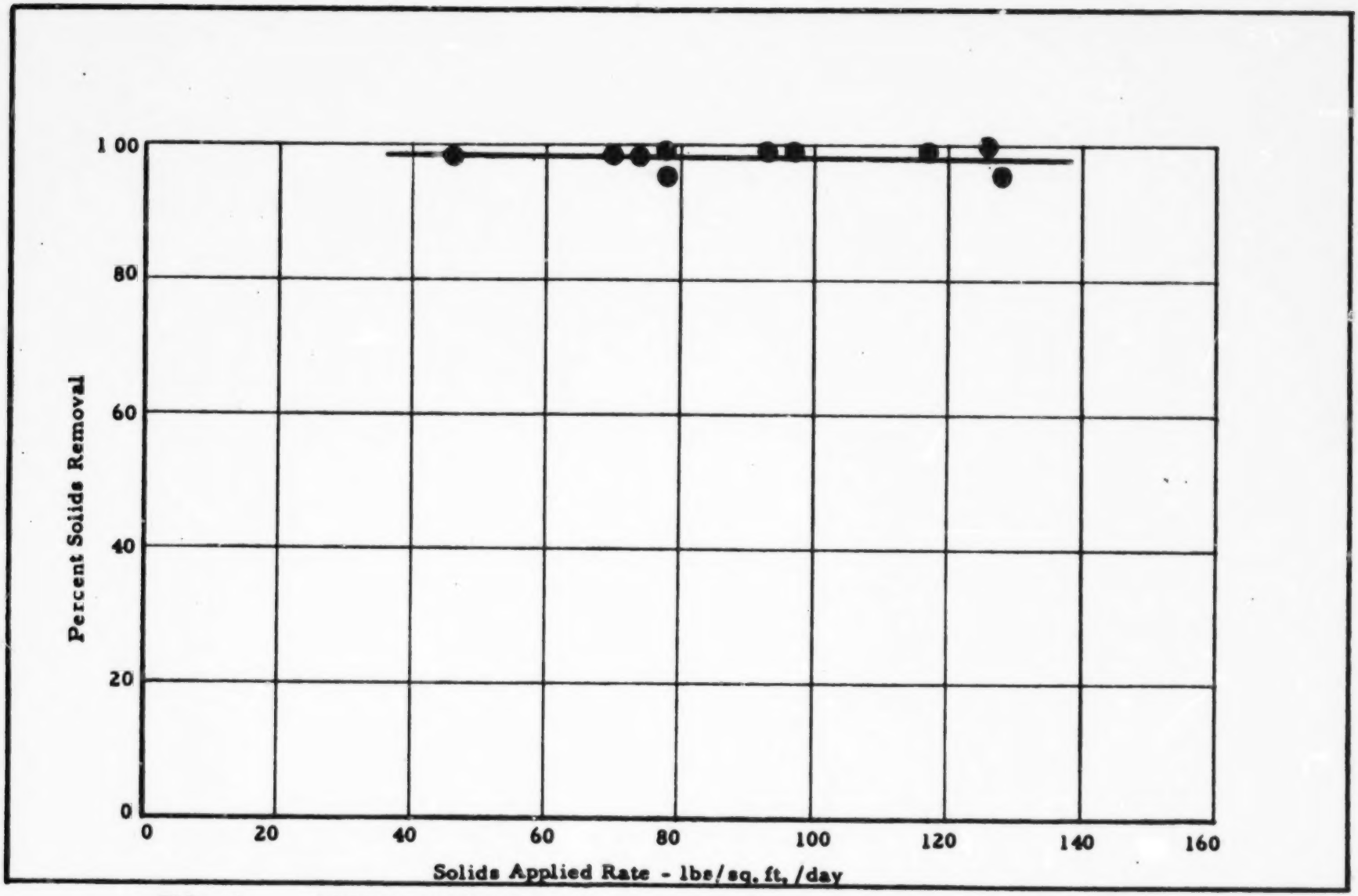


FIG. 45 EFFECT OF SOLIDS APPLIED RATE ON PERCENT SOLIDS REMOVAL FOR ANAEROBIC SLUDGE - SERIES 1

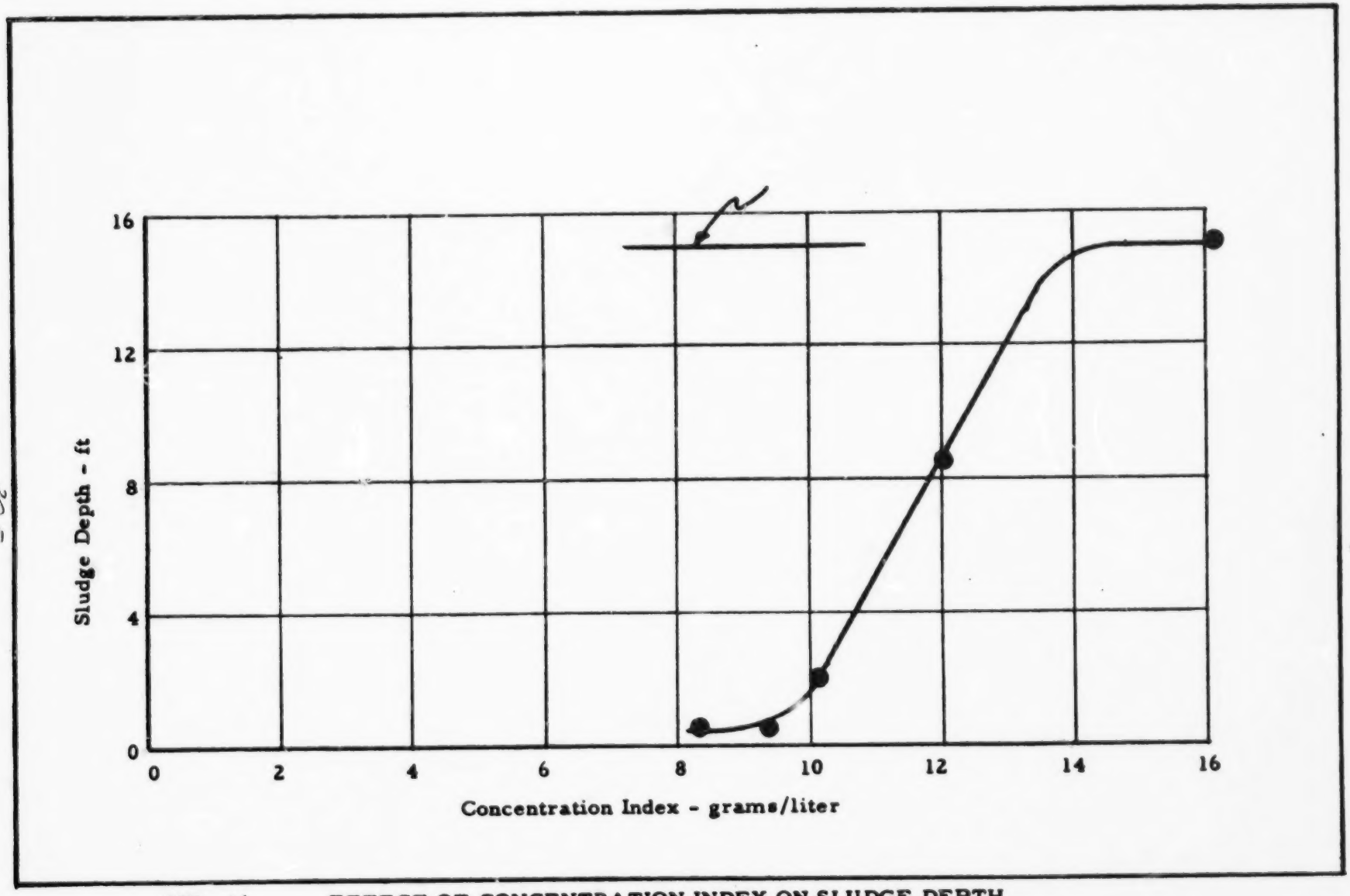


FIG. 46 EFFECT OF CONCENTRATION INDEX ON SLUDGE DEPTH FOR ANAEROBIC SLUDGE - SERIES 2

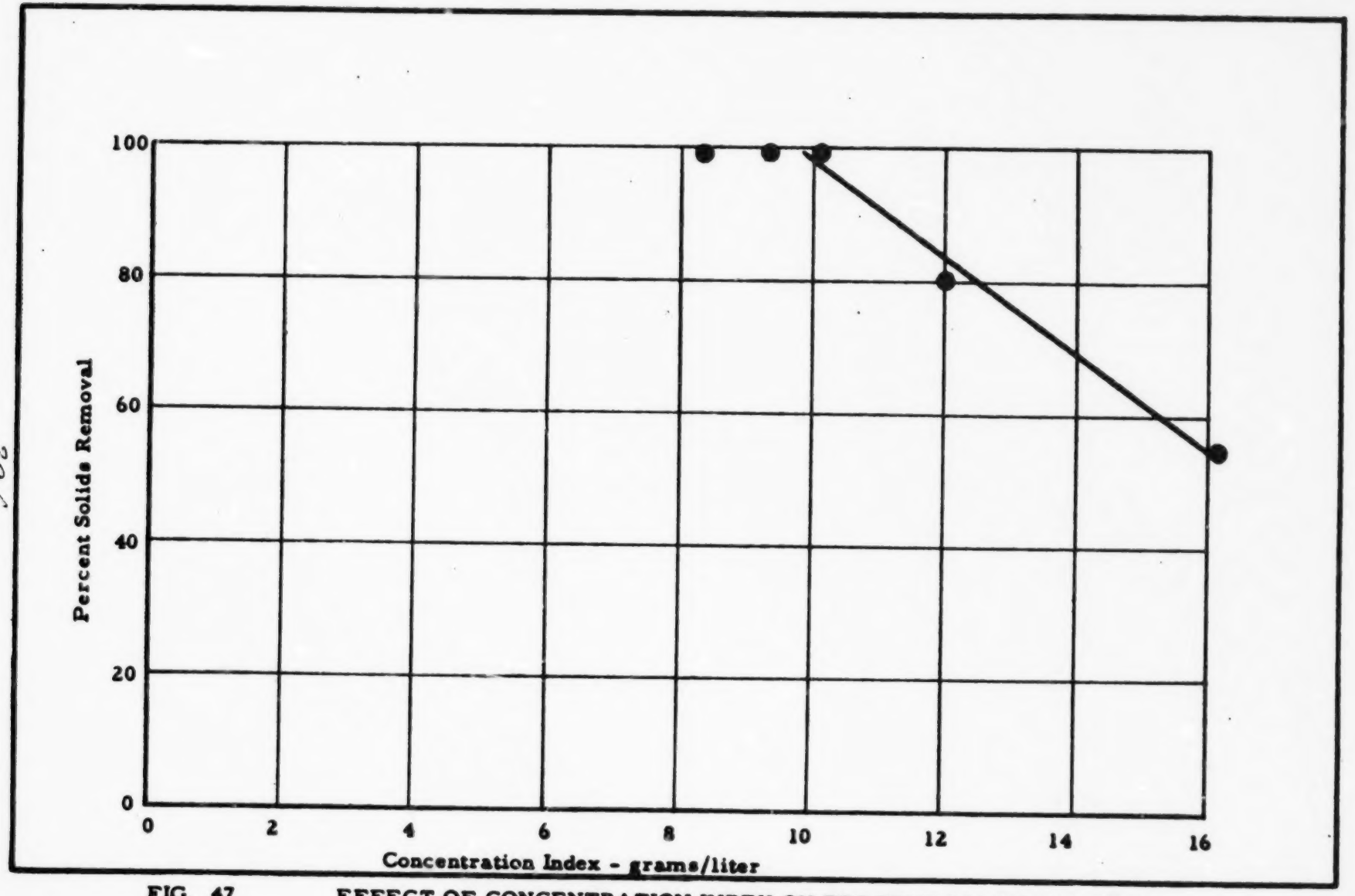


FIG. 47 EFFECT OF CONCENTRATION INDEX ON PERCENT SOLIDS REMOVAL FOR ANAEROBIC SLUDGE - SERIES 2

I. INVESTIGATIONS ON ACTIVATED SLUDGE

1. General

Thickening investigations were made on activated sludge at the municipal waste treatment plant at Mora, Minnesota. The treatment plant is a Chicago pump diffused air conventional activated sludge plant which was being operated at about average loading conditions. For the batch and continuous flow thickening tests the activated sludge was pumped directly from a sampling well in the return sludge line.

2. Characteristics of Activated Sludge

The sludge used in these tests was a typical activated sludge which was brown in color and quite flocculent in nature. The solids concentration of the sludge samples varied from about 4000 to 8000 mg/liter during these tests but were generally in the range of 4000 to 6000 mg/liter. The results of the batch settling tests indicated that the settling characteristics of the sludge remained reasonably constant during the tests. It was also noted that the supernatant was very clear and was biologically stable (no gas bubbles or floating solids) for a period of 1-1/2 to 2 hours. The specific gravity of the dry solids was measured a number of times and ranged from 1.3 to 1.6 with an average of 1.4.

3. Experimental Results on Activated Sludge

a. General

The experimental procedures used in conducting batch and pilot tests on activated sludge were the same as described earlier. As in the case of anaerobic sludge, however, it was found that due to the relatively short detention times, equilibrium could be achieved using a pilot plant run of 6 to 8 hours. Also since the solids concentrations in the sludge

appear to fluctuate in a somewhat cyclic manner the average raw feed solids was based on a composite sample taken at one half hour periods.

b. Batch Test Results

Batch tests were conducted during each pilot plant test, one test at the raw feed solids concentration and one diluted 1 to 1 with plant effluent. These were run on a grab sample taken at the beginning of the test run. An analysis of the results of the batch test taken at the beginning of pilot plant test M-3 will be used as an example. The computed batch flux curve and the bottom and interface solids concentrations are shown in Figures 48 and 49. As in the case of anaerobic sludge these tests were not carried out at a low enough solids concentrations to determine the shape of the flux curve at concentrations below .2%. The flux curve has been extrapolated (shown as a dotted line in Figure 48) based on some of the other settling tests which indicated the critical solids concentration for the formation of a defined interface was about .2%. The results shown in Figure 49 indicate a value for (C_u) of about 2% for this test. In general the value of (C_u) for this batch test series ranged from 1.4 to 2.0% and averaged about 1.5%.

The solids gradient diagram for pilot plant test M-3 is presented in Figure 50 and the total flux curve has been developed and is shown on Figure 48. Since the entire total flux curve is above the raw solids loading line it is evident that there would be no solids loss in the overflow and there would not be an intermediate zone in the solids gradient for this test.

c. Pilot Plant Results

Out of a total of 34 pilot plant tests conducted in this series only 24 tests achieved a reasonable solids balance. The results of these tests

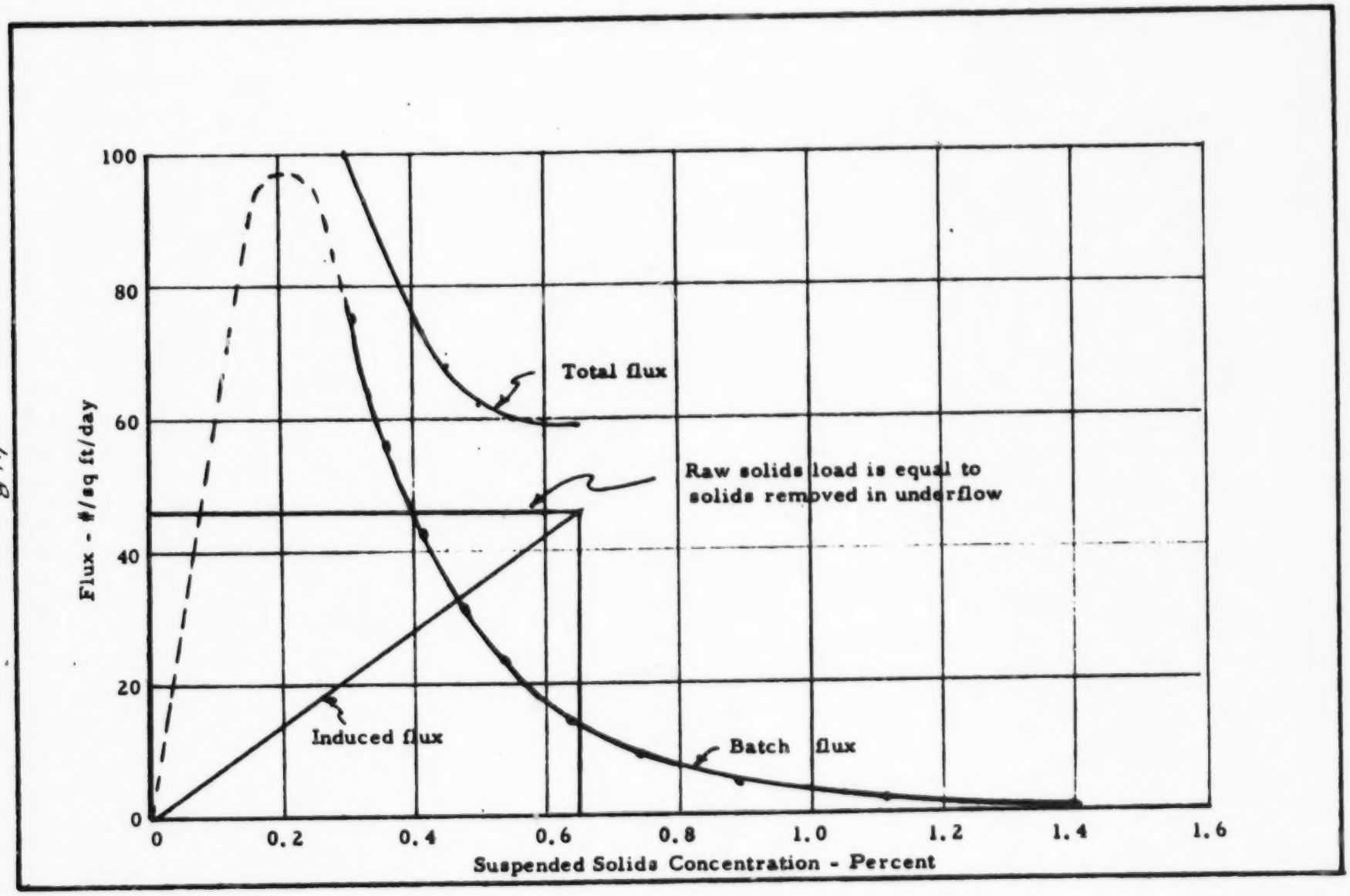


FIG. 48 FLUX CURVES FOR PILOT PLANT TEST NO. M3

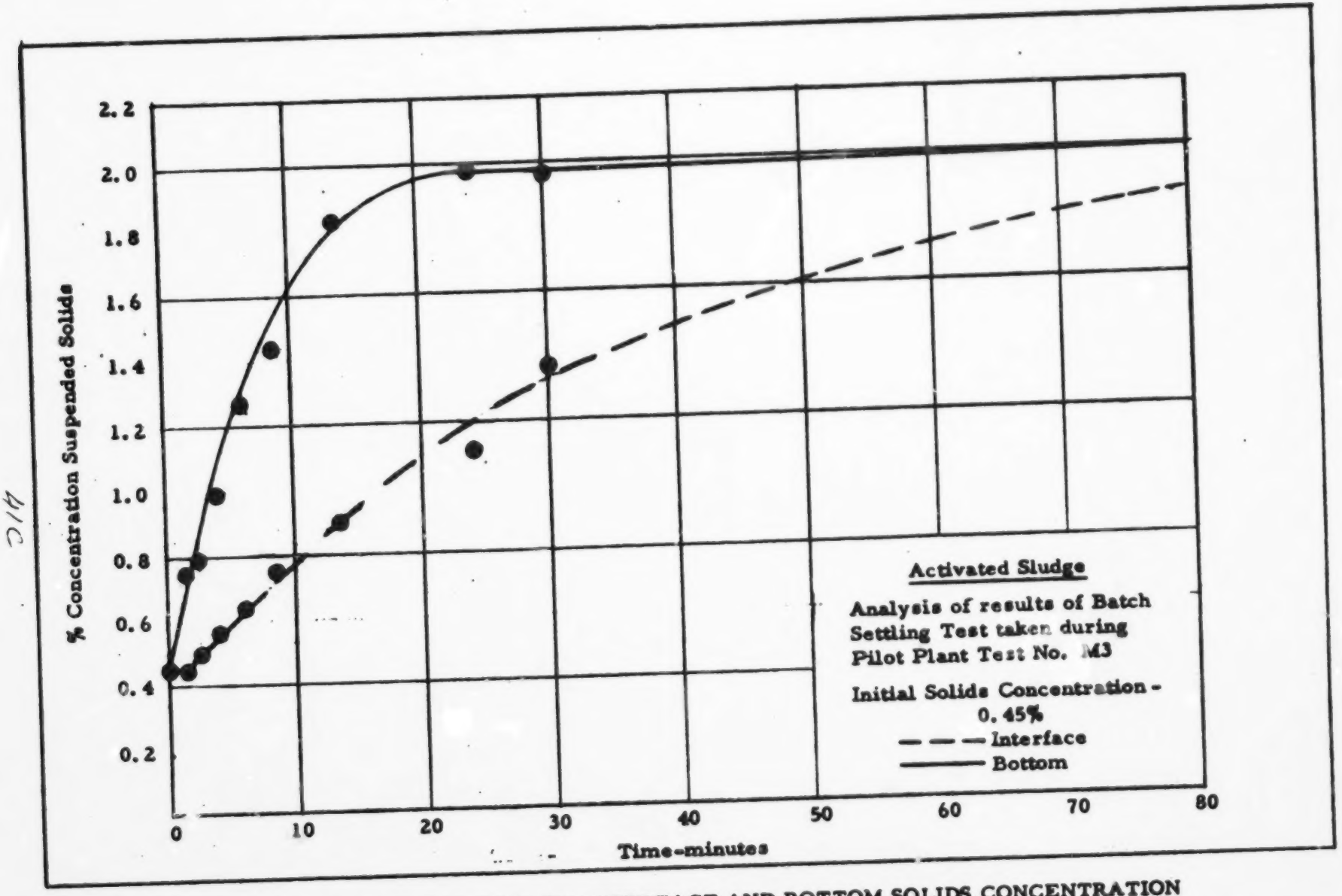


FIG. 49 EFFECT OF SETTLING TIME ON INTERFACE AND BOTTOM SOLIDS CONCENTRATION FOR BATCH TEST TAKEN DURING PILOT PLANT TEST NO. M3

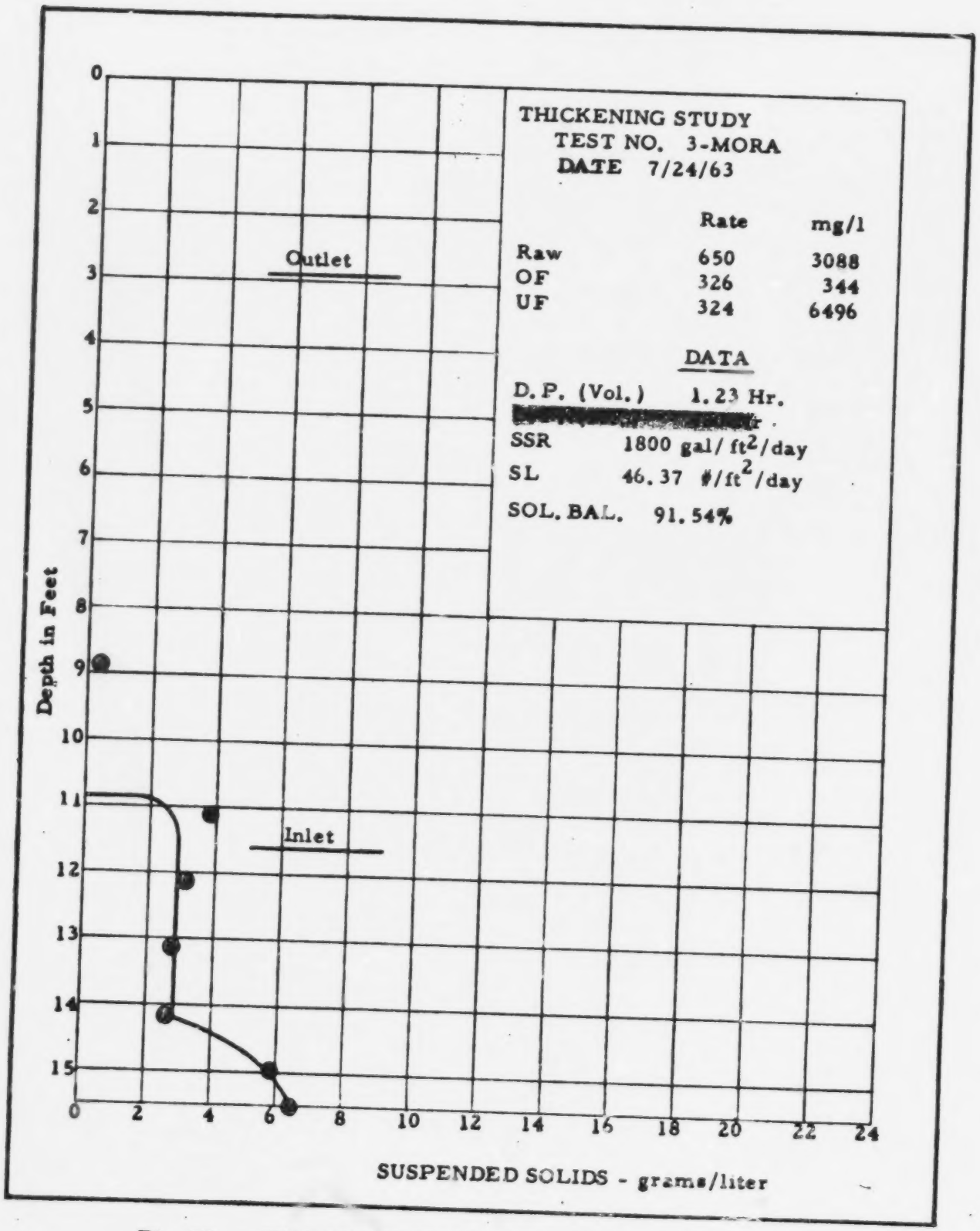


Fig. 50 SUSPENDED SOLIDS GRADIENT IN SLUDGE BLANKET FOR PILOT PLANT TEST NO. M-3

are shown in Table 7. In analyzing the results of these tests, the data were divided into two groups. In Series 1 the solids loading was varied at a relatively constant value of CI and in Series 2 the value of CI was varied at a relatively constant solids loading. The effect of solids applied rate on sludge depth and solids removal for Series 1 is shown in Figures 51 and 52 and the effect of CI on sludge depth and solids removal for Series 2 is shown in Figures 53 and 54. These results indicate a limiting solids applied rate of about 90 lb/sq ft/day and a maximum concentration index of 12 to 16 grams/liter (1.2 to 1.6%) in order to prevent solids loss in the overflow.

TABLE 7

SUMMARY - PILOT PLANT THICKENING EXPERIMENTS
ACTIVATED SLUDGE

Test No.	Flow Ratio	Susp. Sol. mg/l Raw	Susp. Sol. mg/l O.F.	Susp. Sol. mg/l U.F.	Solids Bal. %	Det. Per. Hrs.	SSR *	SAR *	Flow Ratio X SAR	Conc. Index mg/l	Sol. Rem. %	Sludge Depth ft.
M-1	1.81	4470	16	8092	100.00	3.93	562	21.4	38.8	8100	99.92	1.0
M-2	1.99	4248	164	9128	91.40	1.85	1191	42.2	84.0	8440	97.86	1.3
M-3	2.00	3088	344	6496	91.54	1.23	1800	46.37	92.8	6176	88.20	1.3
M-4	2.18	6475	4440	9700	100.00	0.68	3246	175.8	382.5	14100	95.10	12.3
M-5	1.99	5840	2460	9228	100.00	0.92	2388	116.2	231.5	11600	83.30	12.3
M-6	2.00	5516	584	10204	102.26	1.23	1800	82.75	165.50	10032	94.76	12.3
M-7	2.36	3760	160	8668	100.00	1.20	1843	57.9	136.5	8975	98.46	1.3
M-8	2.86	3510	140	9760	100.00	1.29	1709	50.0	143	10020	98.20	1.7
M-9	3.49	5060	2744	11900	100.00	1.21	1817	77.0	308	20300	58.25	5.5
M-10	3.93	6268	3984	12032	103.89	1.22	1806	94.40	371	24600	53.60	12.3
M-11	4.50	4552	2480	13740	94.61	1.23	1795	68.14	306.5	20500	70.4	12.3
M-15	2.04	5588	300	10040	109.8	1.22	1810	84.2	171.8	11400	97.27	2.5

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TABLE 7 (Cont'd.)

Test No.	Flow Ratio	Susp. Sol. mg/l Raw	O. F.	U. F.	Solids Bal. %	Det. Per. Hrs.	SSR *	SAR *	Flow Ratio X SAR	Conc. Index mg/l	Sol. Rem. %	Sludge Depth ft.
M-18	1.99	6804	2228	10392	107.5	1.23	1800	102.1	203.8	13550	83.7	2.3
M-20	3.03	8096	6340	10180	106.7	1.23	1210	121.0	366.5	24450	47.50	2.3
M-21	3.46	6592	2604	14228	110.54	1.23	1790	98.5	340.5	22800	71.80	12.3
M-22	4.01	5132	2316	11508	111.40	1.22	1811	77.5	310.5	20600	66.0	12.3
M-23	1.59	4540	64	7224	99.4	1.54	1430	54.1	86.0	7230	99.50	1.0
M-24	1.76	3828	128	5792	104.5	1.13	1958	62.5	110.0	6920	98.75	1.0
M-26	1.61	3784	128	7436	81.5	0.74	2980	94.0	151.0	6100	98.72	11.7
M-27	1.93	4352	116	7304	113.9	1.58	1400	50.75	97.9	8440	98.71	2.0
M-28	2.34	3804	0	7604	117.1	1.58	1340	44.4	103.9	9150	100.00	2.0
M-29	3.15	5272	292	12252	128.9	1.55	1370	62.6	197.2	16600	96.20	12.3
M-30	4.02	4388	136	15248	112.5	1.50	1420	53.8	216.3	17650	97.67	12.3
M-31	4.74	4048	16	19200	100.0	1.56	1418	47.9	227.0	19200	99.69	10.5

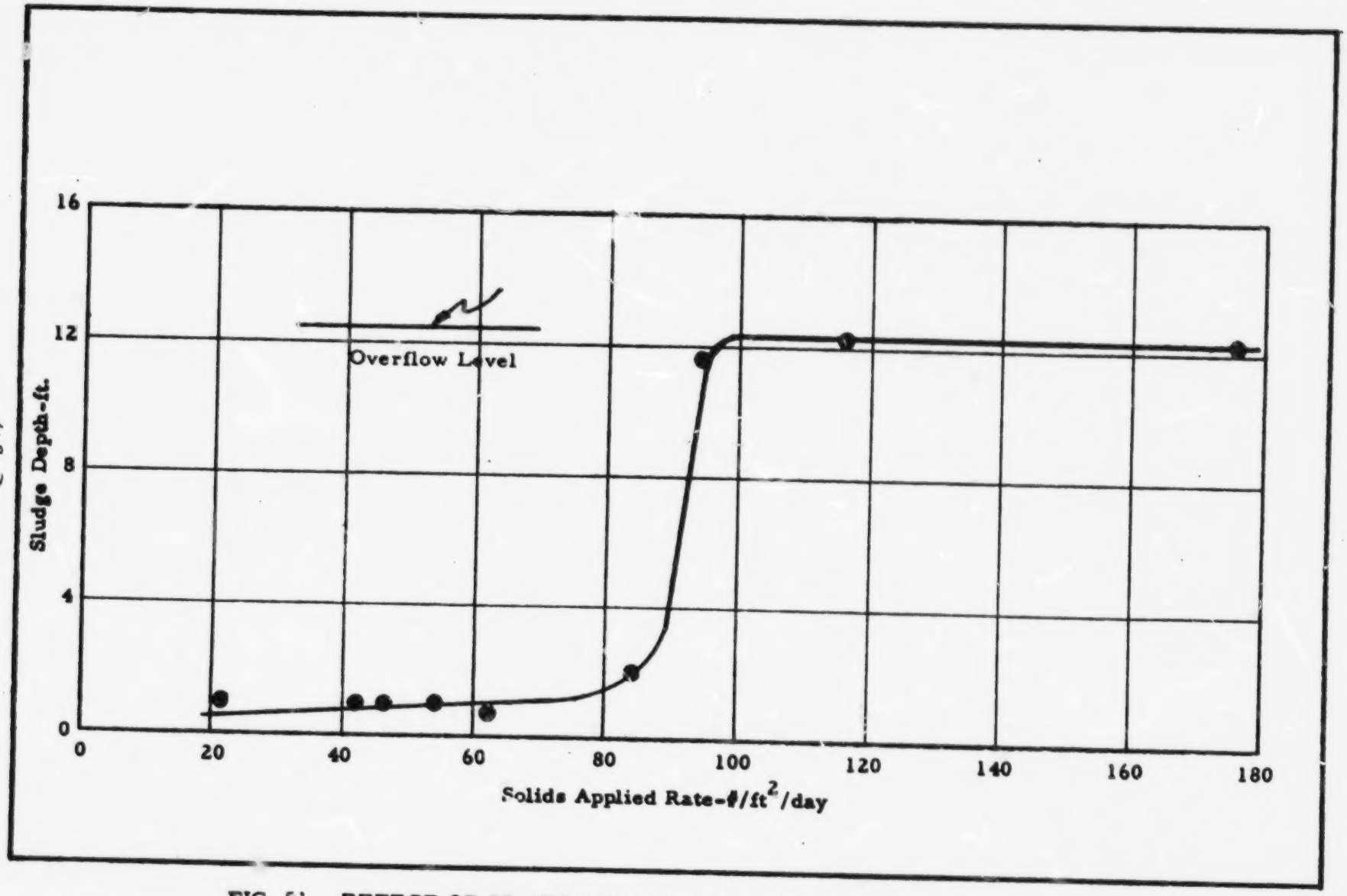


FIG. 51 EFFECT OF SOLIDS APPLIED RATE ON SLUDGE DEPTH FOR ACTIVATED SLUDGE - SERIES 1

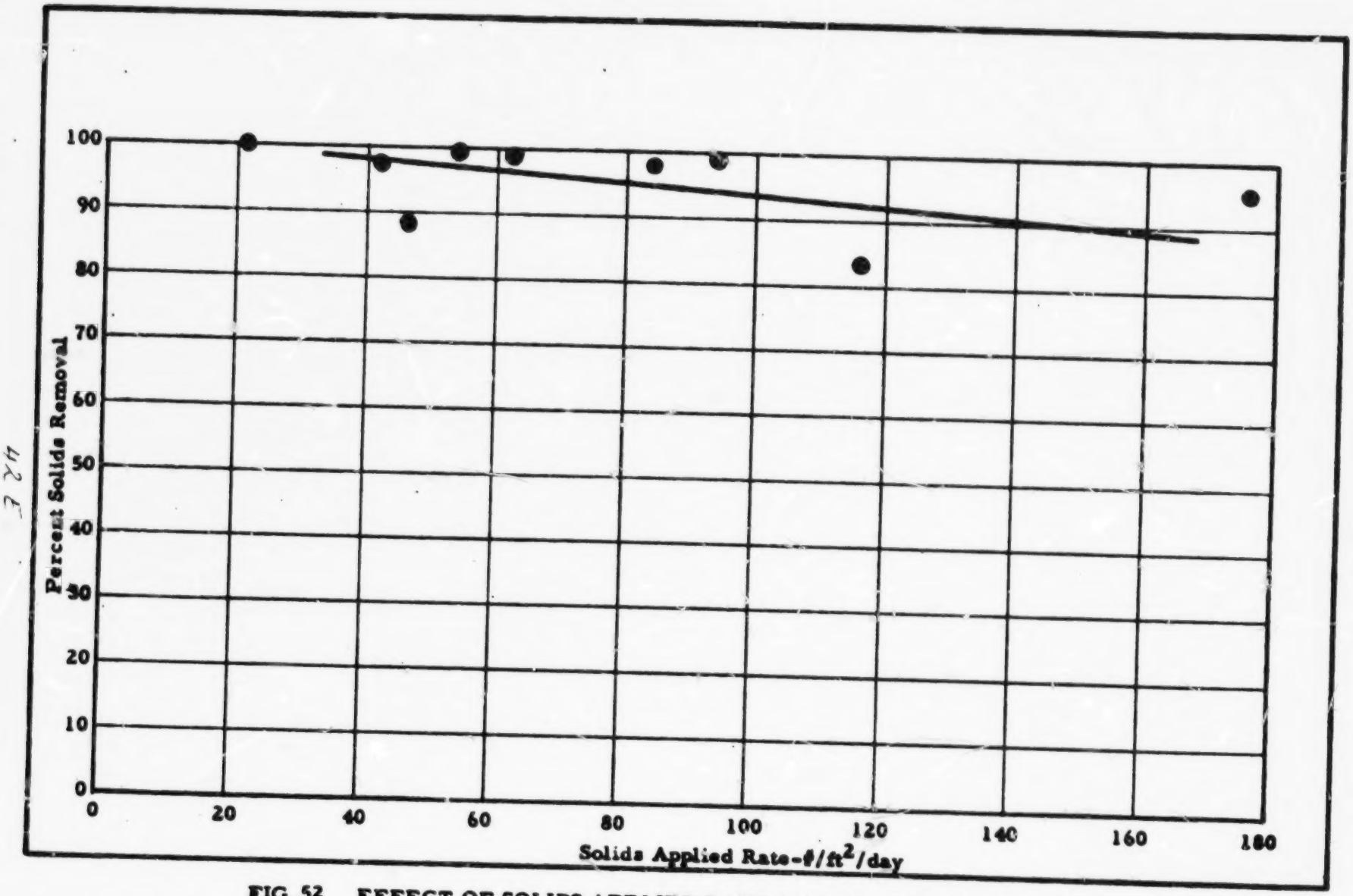


FIG. 52 EFFECT OF SOLIDS APPLIED RATE ON PERCENT SOLIDS REMOVAL FOR ACTIVATED SLUDGE - SERIES 1

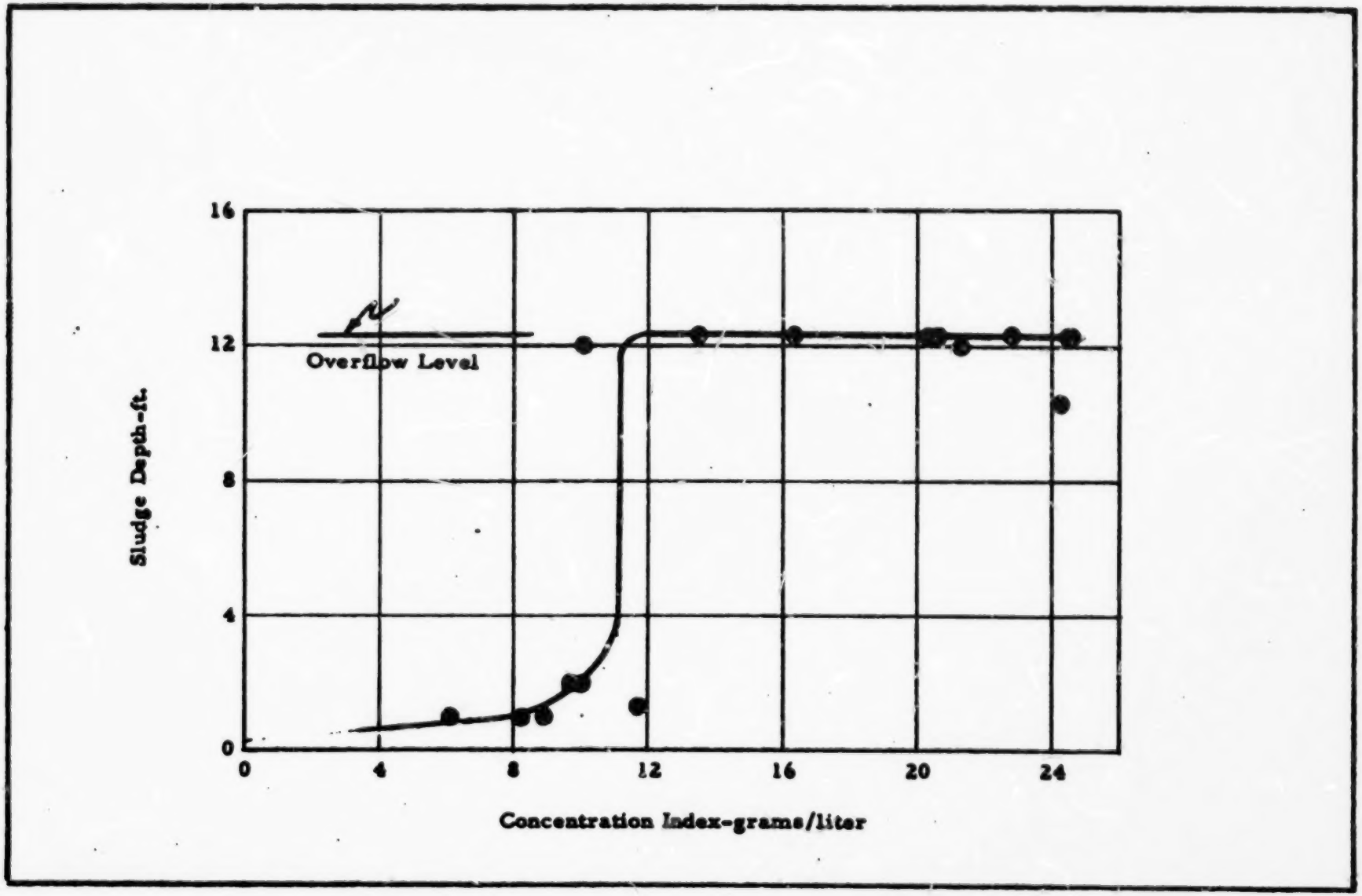


FIG. 53 EFFECT OF CONCENTRATION INDEX ON SLUDGE DEPTH FOR ACTIVATED SLUDGE - SERIES 2

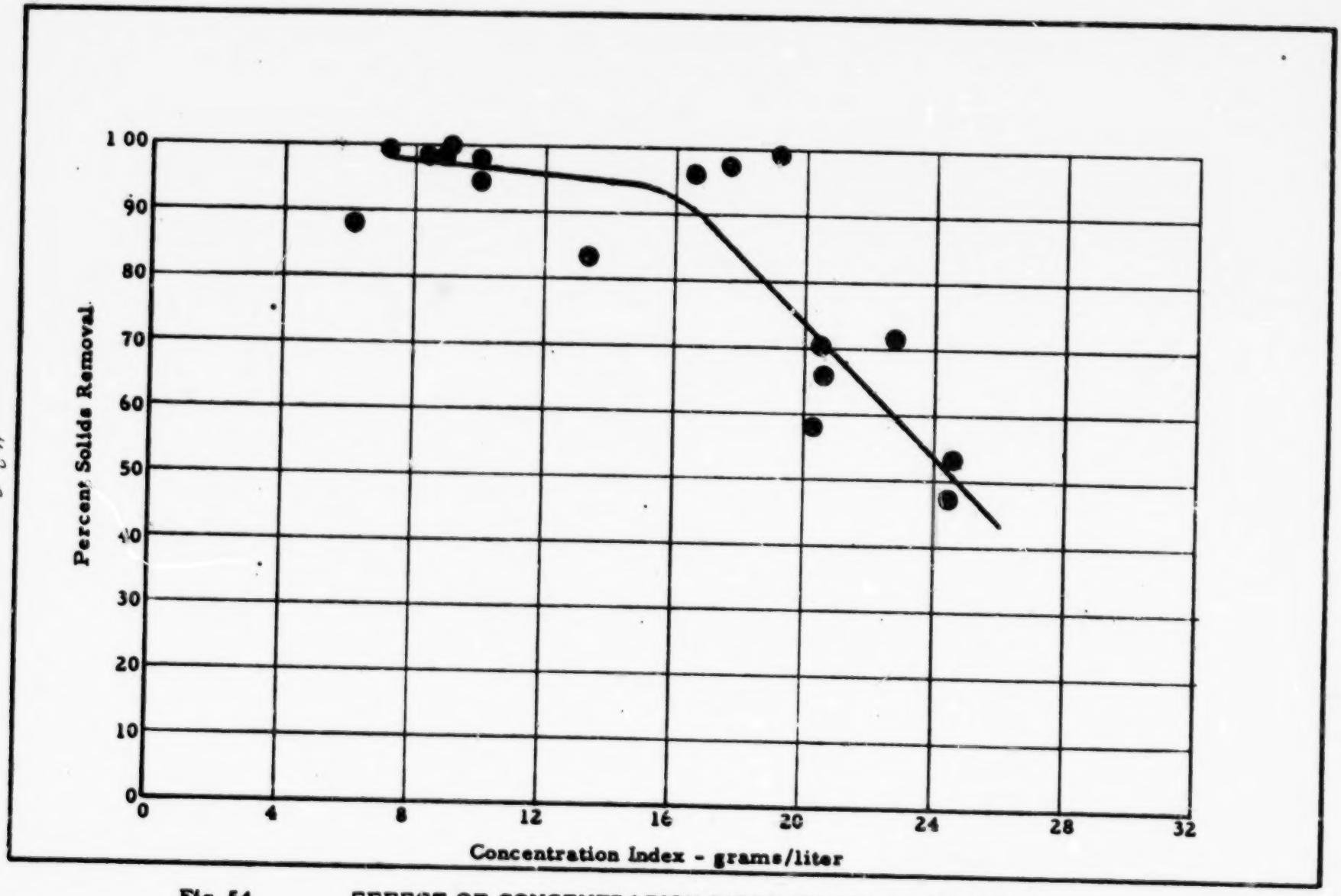


Fig. 54 EFFECT OF CONCENTRATION INDEX ON SOLIDS REMOVAL FOR ACTIVATED SLUDGE - SERIES 2

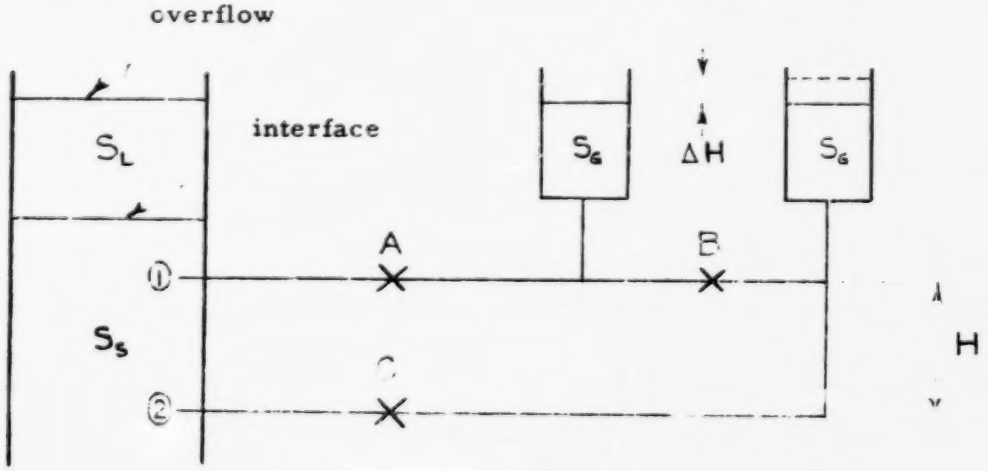
J. ANCILLARY INVESTIGATIONS ON SLUDGE DENSITY METER

1. General

The solids concentration gradient along the depth of a thickener operating under continuous steady state conditions was believed to be related to the mechanisms which occur in the thickener. For this reason, sample taps were provided at 4 inch intervals along the length of the pilot thickening unit. The long time required to take samples and determine the solids by the drying method on such a large number of samples for each test initiated work on the development of a sludge density meter which could be used to quickly determine the solids gradient in a continuous flow thickener. Two methods were investigated, one was based on measuring small pressure differentials at taps spaced at intervals in the sludge blanket, the other was based on the weight differentials of a hanging constant volume weight which could be lowered into the sludge blanket.

2. Pressure Method of Measuring Sludge Concentration

The basic idea of this method is based on manometry and can probably be best explained by developing the mathematics of the method. Suppose a continuous thickener is operating under steady state conditions with an overflow level and sludge interface as shown in the diagram below.



Assume that the specific gravity of the liquid in the gage is S_G, the specific gravity of the suspending liquid is S_L, the dry specific gravity of the solids is S_S and that the solids concentration between points (1) and (2) is constant or varies linearly with depth. Then with liquid level in the gage tubes slightly higher than the overflow level in the thickener, if clamps A and B are opened with C closed the levels in the gage tubes will be balanced at the same level and will reflect the pressure at point (1). Now if clamp B is closed and C is opened the level in the right hand gage tube will rise ΔH, reflecting the pressure due to the difference in weight of the column of sludge between (1) and (2) in the thickener and the column of liquid (H) in the gage. The average concentration of solids between (1) and (2) can be computed based on the change in head (ΔH). Using the following definition of terms,

H = distance between sample taps, inches

ΔH = change in head of gage, inches

S_L = specific gravity of suspending liquid

S_G = specific gravity of gage liquid (usually water)

S_S = specific gravity of solids in sludge

C = concentration of solids in sludge, mg/l

it can be shown by manometry that

$$C = \frac{\Delta H}{H} \quad \frac{S_G}{1 - \frac{S_L}{S_S}} - \frac{(S_L - S_G)}{\left(1 - \frac{S_L}{S_G}\right)} \times 10^6 \text{ (mg/liter)}$$

Thus the accuracy with which the solids concentration can be determined by this method is dependent on how accurately the change in head ΔH can be determined. It is also important to determine the average values for H, S_L, S_G, and S_S. In most of the investigations reported herein the suspending liquid and the gage fluid were essentially pure water. As an example of the effect of ΔH, H & S_S on solids concentration, Table 8 below has been

computed from the above equation assuming S_L and S_G were equal to 1.000.

TABLE 8

Concentration of Solids (mg/liter) at Various Values of ΔH, H and S_S

(Assuming S_L and S_G = 1.000)

S_S	ΔH					
	.001 inch			.0005 inch		
	H			H		
	4 in	8 in	12 in	4 in	8 in	12 in
1.25	1250	625	417	625	312	208
1.50	750	375	250	375	188	125
1.75	584	292	195	292	146	98
2.00	500	250	168	250	125	84
2.25	450	225	150	225	112	75
2.50	417	208	139	208	104	68
2.75	393	196	131	196	98	65

Since most of the thickening tests were at fairly high solids concentration (generally above 5,000 mg/l) it was felt that this method would be sufficiently accurate for the purposes if a system or instrument could be developed to measure pressure differentials of .001 inch of water or less.

There are a number of manometric instruments commercially available which are able to measure pressure differentials to .001 inch or less. The problem here was to develop a system that would give accurate and stable readings as applied to the pilot plant arrangement and could also be used in the design of a probe type instrument which could be used for measuring concentration gradients in plant scale thickeners. After testing a number of instruments a micrometer point gage manufactured by the F. W. Dwyer Co. was selected for use in the subsequent studies.

The instrument was tested to determine the reproducibility of gage readings under static conditions. The readings were estimated to the nearest .0001 inch. Under these non-flow conditions the readings were found to be reproducible within a standard deviation of $\pm$ .00015 inch. Under flow conditions using pure water and the instrument mounted on the pilot plant, the readings were reproducible within a standard deviation of about $\pm$ .0005 inch. A number of pilot plant tests were conducted on calcium carbonate slurries and water softening sludge in which the solids gradient was measured by the pressure method and at the same time samples were taken at the same points to determine the solids by the drying method. These tests showed a standard deviation of about $\pm$ 4 to $\pm$ 8% between the two methods.

The pressure method for determining solids concentrations in the sludge blanket was used in many of the pilot plant tests. Using the inert suspensions such as calcium carbonate slurries and water plant sludge the method worked very well. However it was found that in the biologically active sludges (aerated supernatant sludge, anaerobic sludge and activated sludge) the method gave very erratic results and could not be used to measure the solids concentrations. This was due to the gas bubbles formed in the sludge which erratically affected the sludge density measurements by this method. Further it was found that the method could not be used effectively on heavy sludges which were able to withstand internal shear stresses (this causes bridging effects and liquid pockets) as in the case of primary sewage sludge and in some cases in the aerated supernatant sludge.

3. Sludge Density Probe

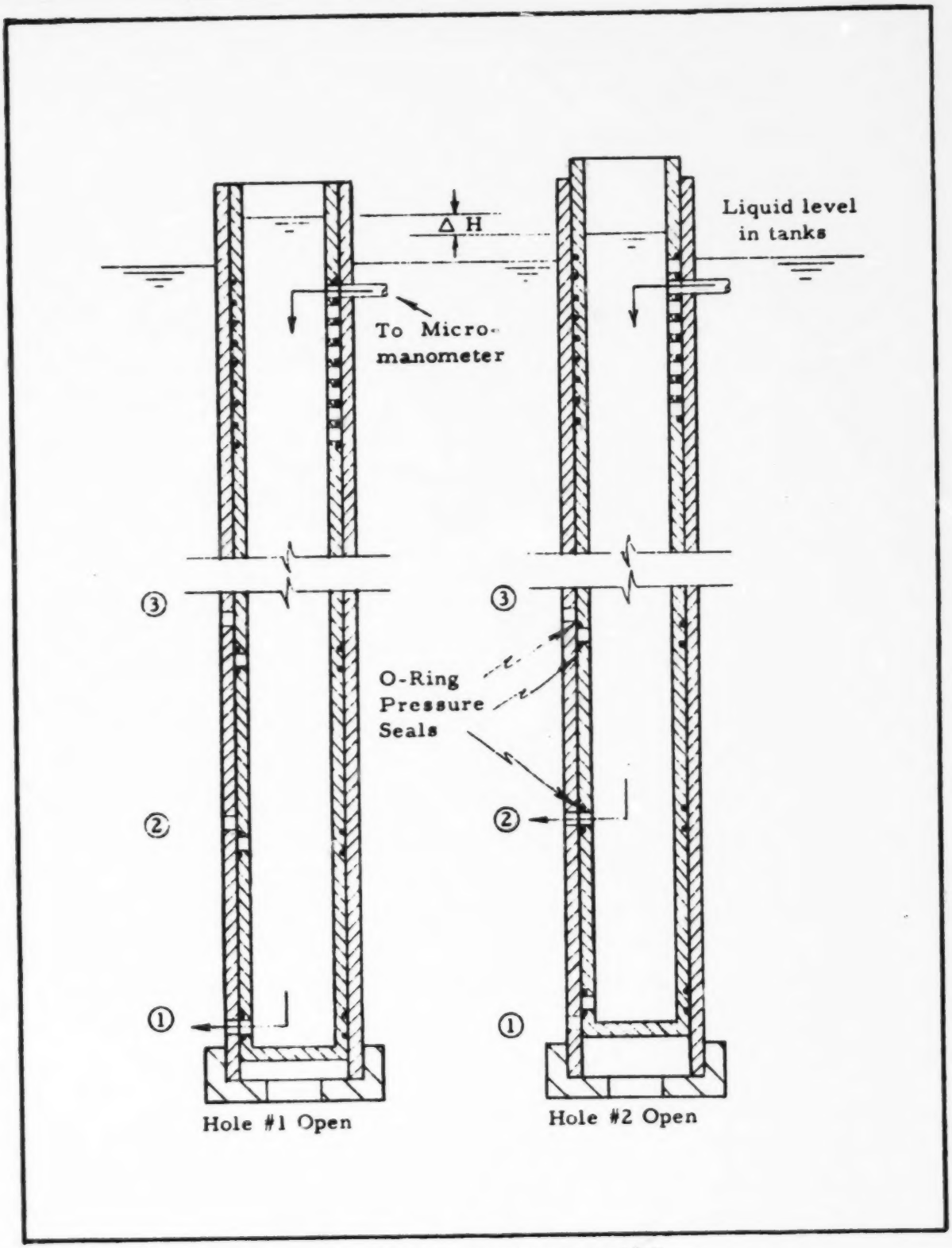
During the last several months of these investigations a probe type instrument was designed and constructed using the micrometer point gage for measuring pressure differentials in a sludge blanket. This

instrument was conceived so that it could hopefully be used as a rapid method of measuring the solids gradients in plant scale thickeners. The design features of this probe are shown in Figure 55. In general the probe consisted of two concentric brass tubes. The inner tube was designed to slide (trombone fashion) while the outer tube remained stationary resting on the bottom of the thickening tank. Pressure taps (1/8 inch diam) were placed at one foot intervals in the outside tube and at 3/8 inch less than one foot intervals on the inner tube. Each tap on the inner tube was sealed on each side with O rings. When the inner tube was at the bottom (not shown in the figure) none of the taps were open to the tank pressure. As the inner tube was raised 3/8 of an inch tap no. 1 was open to the micrometer gage. If the water level in the gage were higher than that of the tank, the water would flow out of tap no. 1 until the equilibrium sludge pressure at this point was reached. The inner tube would then be raised 3/8 of an inch and tap no. 2 would be open to the gage and at equilibrium the water level in the gage would drop ΔH. In this fashion, the pressure differentials could be determined at one foot intervals in the thickening unit.

In general this instrument gave comparable results to those mentioned above for the micrometer pressure differentials taken on the sample taps in the pilot plant. The instrument was tested in plant scale thickeners on water softening sludge, anaerobic sludge and primary sewage sludge. The tests on the inert water softening sludge gave results within 5% of the solids measured by the drying method. However in the case of the biologically active anaerobic sludge the results were very erratic because of gas bubbles in the sludge and in heavy primary sludge the internal shear stresses prevented the proper functioning of the instrument.

4. Sludge Density Balance

Some very preliminary investigations were made on a hanging

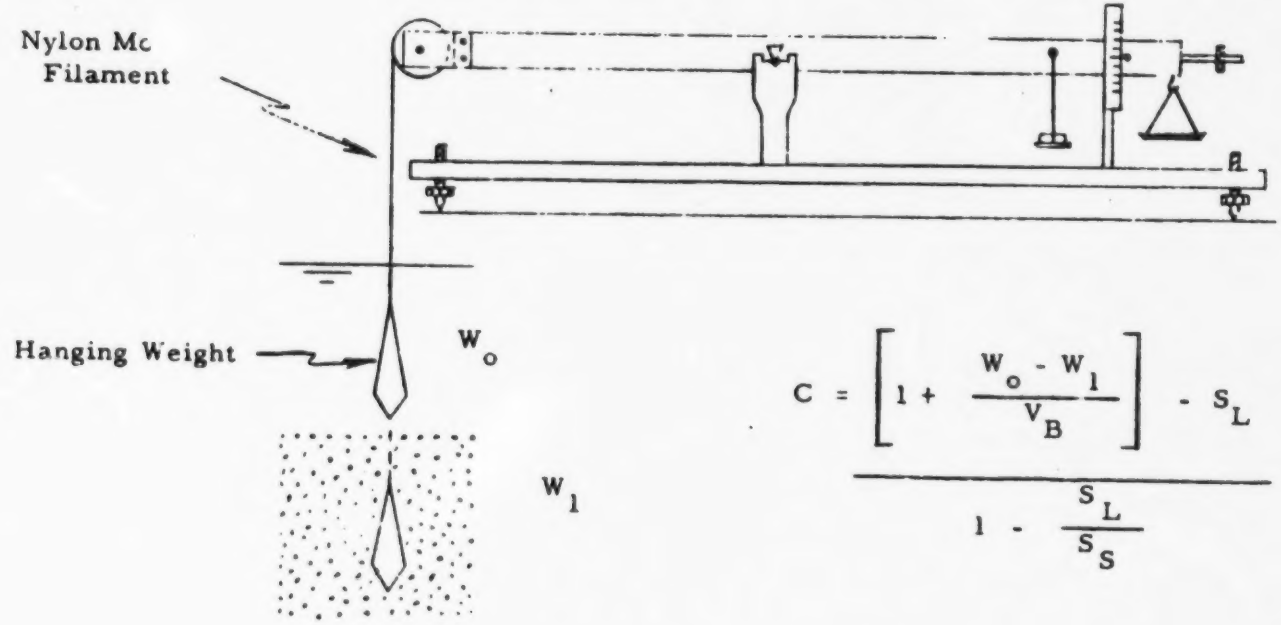


DESIGN OF SLUDGE DENSITY PROBE

FIG. 55

weight sludge density balance. The method is the same as that used in the familiar balance for measuring the specific gravity of liquids. The details of this instrument together with the basis for computing the concentration of solids based on (W_o - W_1), V_B (volume of the hanging weight), the specific gravity of the suspending liquid (S_L) and the specific gravity of the solids (S_S) are shown in Figure 56.

As might have been expected this instrument gave very good results in clear liquids. However when this instrument was tried in the pilot plant with solids settling in the tube the solids tended to adhere to the hanging weight and it was not possible to get accurate readings. For this reason these investigations were discontinued.



$$C = \frac{\left[1 + \frac{W_o - W_1}{V_B}\right] - S_L}{1 - \frac{S_L}{S_S}}$$

48B

FIG. 56 DESIGN OF SLUDGE DENSITY BALANCE

K. SUMMARY AND CONCLUSIONS

The results of these investigations warrant the following summary statements and conclusions.

1. A method was developed, based on a theory developed by C. J. Kynch, for analyzing the results of batch settling tests to determine the settling characteristics of a suspension in terms of the batch or self flux at various concentrations and the ultimate bottom concentration (C_u).

2. An approximate method was developed for applying the results of batch tests for predicting the limiting solids loading and maximum underflow solids concentrations in a continuous flow thickener as applied to a particular solids suspension.

3. Pilot plant tests on a number of different suspensions verified the existence of four zones of solids concentrations that occur in a continuous thickener under certain loading conditions. These zones have been observed and described by other workers. The bottom zone which was described in the past as the rake action zone was found in these tests to be due to the restriction at the bottom of the thickener and would occur, even without the action of rakes or flight scrappers.

4. A possible explanation of the solids concentration in the four zones can be made on the basis of the relationship between the total flux (batch or self flux plus induced flux due to underflow) at various concentrations and the solids loading.

5. The factors affecting the depths of these various zones have not been clearly indicated by the results of these investigations. The bottom or underflow concentration is most likely a direct function of the depth of the bottom (or compaction) zone. The excess weight of solids above the bottom would tend to squeeze more liquid out of the sludge. It was found in these investigations however that with the exception of calcium carbonate slurries, the bottom concentration was increased very slightly if at all at higher depths especially as applied to flocculent organic solids.

6. With respect to the continuous flow pilot plant studies on a number of different suspensions it was found that the most significant loading parameters affecting the performance of the thickener were (a) the solids applied rate (SAR in lb/sq ft/day) and (b) a parameter which has been designated herein as the concentration index.

7. The results of batch test series on six different solids suspensions or sludges were used to predict the following limiting loading conditions to avoid the loss of solids in the overflow in a continuous flow thickener.

	Maximum Batch Flux, lb/sq ft/day	C_u % Solids
1) Calcium Carbonate	400 to 450	50 to 60
2) Water Softening Sludge	150 to 175	6 to 7
3) Aerated Supernatant Sludge	not determined	4 to 6
4) Primary Sludge	60 to 80	6 to 8
5) Anaerobic Sludge	100 to 120	1.3 to 1.5
6) Activated Sludge	80 to 100	1.4 to 2.0

8. The continuous flow pilot plant test series on the six suspensions indicate the following limiting loading conditions on the thickener to avoid the loss of solids in the overflow.

	Maximum SAR lb/sq ft/day	Maximum Concentration Index % Solids
1) Calcium Carbonate	300 to 350	50 to 60
2) Water Softening Sludge	150	6 to 7
3) Aerated Supernatant Sludge	30 to 40	4 to 5
4) Primary Sludge	50 to 55	6 to 7
5) Anaerobic Sludge	130	1.2 to 1.4
6) Activated Sludge	90	1.2 to 1.6

9. A rational method for designing and operating a continuous flow thickener for a particular sludge would be to conduct a series of batch tests to determine the maximum batch flux, and the maximum C_u. The thickener would then be designed to operate at a solids loading and concentration index somewhat below these figures. With respect to depth of the thickener, within practical limits it does not appear economical to provide very deep thickeners especially when thickening is applied to light flocculent suspensions.

10. A method based on measuring small pressure differentials has been developed to measure the solids gradient in a continuous flow thickener. Also a probe type of instrument for measuring solids gradients in plant scale thickeners and using the pressure method has been developed. In all of the tests on inert suspensions the standard deviation of this method as compared to the drying method for determining solids concentrations was found to be less than $\pm$ 10%. However it was found that the instrument could not be used in biogically active sludges because of gas bubbles or in heavy sludges that would support internal shear forces and as a result not transmit the pressure.

BIBLIOGRAPHY

1. Coe, H. S. and Clevenger, G. H. "Methods for Determining the Capacities of Slime-Settling Tanks". Trans. Am. Inst. Mining-Met. Engrs. 55, 356 (1916).

2. Darby, G. M. and Bull, A. W. "The Pre-Sedimentation of Turbid Water Supplies". Trans. Am. Inst. Chem. Engrs. 18, (1926) pp. 365-378.

3. Comings, E. W., Priss, C. E. and DeBord, C. "Continuous Settling and Thickening". Ind. and Eng. Chemistry. 46, 8:1164 (1954).

4. Kynch, G. J. "A Theory of Sedimentation". Trans. Farad. Soc. (1952) 48, 166.

5. Talmadge, W. P. and Fitch, E. B. "Determining Thickener Unit Areas". Ind. and Eng. Chemistry. 47:38 (1955).

6. Behn, V. C. "The Sludge Thickening Operation in Sewage Treatment". Doctoral Dissertation, Dept. of Sanitary Eng. and Water Resources. John Hopkins University, 1953.

7. Hassett, N. J. Part I: "Design and Operation of Continuous Thickeners". The Industrial Chemist. (March, 1958).

8. Hassett, N. J. Part II: "Design and Operation of Continuous Thickeners". The Industrial Chemist. (April, 1958).

9. Hassett, J. J. Part III: "Design and Operation of Continuous Thickeners". The Industrial Chemist. (September, 1958).

10. Wise, W. S. "The Theory of the Operation of Continuous Thickeners". The Industrial Chemist. (February, 1960).